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A R M S T R O N G L A B O R A T O R Y

# CHOICE BIMANUAL AIMING WITH UNEQUAL INDICES OF DIFFICULTY (U)



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**FOR THE COMMANDER**

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Human performance response times are typically predicted using two models. Hick's Law, used to predict reaction time (RT), linearly relates RT to the information content of the stimulus. Fitts' Law linearly relates movement time (MT) to the difficulty (ID) of the particular task.

Three studies were conducted to characterize temporal bimanual aiming performance. Pilot Study I verified Hick's and Fitts' Laws for unimanual tasks only. Pilot Study II established the validity of the stimulus-response board used as a testbed for bimanual tasks. The Main Study tested discrete, unimanual and bimanual visual aiming tasks. The number of target alternatives (N) varied to test Hick's Law. Task difficulty varied by changing movement amplitude and target width to test Fitts' Law.

All task performance was affected by changing task difficulty of the opposite hand (OPID) for both the easy and difficult task hands. Both laws held under bimanual tasking with OPID held constant. RTand MT lengthened with increasing N, ID, and OPID. RT and MT were positively correlated for all bimanual tasks under all conditions. Results also showed little reaction and movement synchrony between hands. Multiple linear regression was used to examine RT, MT and total response time (TRT) bimanual models.

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## ABSTRACT

Human performance response times to stimuli are typically predicted using two models first developed in the 1950's. Hick's Law, used to predict reaction time (RT), linearly relates RT to the information content of the stimulus. Movement time (MT) is also predicted using an information-theoretic model known as Fitts' Law which linearly relates MT to what Fitts called the index of difficulty (ID) of the particular task. These laws have been found to be quite robust in predicting RT and MT, respectively, for unimanual visual aiming tasks. Previous research involving bimanual aiming tasks has reported violations of Fitts' Law when the two hands are moving to targets of differing difficulty with only the easy-task hand slowing. Results have been inconsistent on the issue of whether the hands react and move in synchrony.

Three studies were conducted to characterize temporal human bimanual aiming performance. Pilot Study I verified Hick's and Fitts' Laws for unimanual tasks only. Pilot Study II established the utility of the stimulus-response board that was used as a testing medium for bimanual tasks. Hick's Law and Fitts' Law held for the new apparatus. The Main Study tested twenty subjects performing discrete, unimanual and bimanual visual aiming tasks. The number of target alternatives was varied to test Hick's Law and task difficulty was varied by changing movement amplitude and target width to test Fitts' Law. Each combination of number of target alternatives, ID, and opposite hand ID (OPID) was tested.

Hicks' Law and Fitts' Law held under bimanual tasking with OPID held constant. However, all task performance was affected by changing the task difficulty of the opposite hand for both the easy and difficult task hands. Reaction times and movement times lengthened as the number of target alternatives increased, and as ID and OPID increased. RT and MT were positively correlated for all bimanual tasks for all hands, target alternatives, ID and OPID conditions. Results also showed little reaction and movement synchrony even when the hands were similarly tasked. Multiple linear regression was used to examine RT, MT and total response time (TRT) bimanual models.

# CHAPTER I

## INTRODUCTION

The interaction of people with functional devices typically involves physical activity of the limbs. The arm-hand system is used to manipulate steering wheels and levers and to activate knobs and switches. The extent of the involvement as well as the levels of force, speed and skill required depends on the device manipulated and the human-device interface. Control of the hand-arm system thus represents a vital output link from the human to the device.

Prior to the operation of a control, the hand must move to the control and contact the appropriate control surface. If a large number of controls exists, or the operator must activate a series of controls in succession, or the controlled function is critical to safe and efficient system operation, then the speed and accuracy of the aimed reaching movements are vital.

Human speed and accuracy limitations have been the object of much scientific study. Determining the limits of the human ability to respond quickly and correctly with the tools available in a given situation and environment provides system designers much needed information to complement their knowledge of physical system limitations. Characterization and modeling of these human limitations is essential for optimizing human performance within the system.

This dissertation provides a characterization of aimed movement performance for

one-handed (unimanual) and two-handed (bimanual) choice response tasks. Modeling of aimed movement performance is presented within the context of Hick's Law which models reaction time as a function of the information content of the stimulus and Fitts' Law which models movement time as a function of the amplitude and accuracy requirement of the movement.

### 1.1 Input - Cognition - Output

From a theoretical standpoint, human information processing can be viewed as occurring in three stages: *input*, *cognition*, and *output* (Sternberg, 1969; Schmidt, 1988; Wickens, 1992). For the stimulus-response event to take place, input of stimulus information must first occur. That is, the stimulus event and message must be received by the senses (visual, auditory, proprioceptive and kinesthetic systems) before any response can be produced. Successful input implies that the stimulus has been detected and discriminated from environmental noise.

Once stimulus (signal) detection has occurred, *cognitive processing* takes place where perception interacts with short-term and long-term memory at levels of greater complexity. This leads to a process of perceptual decision where recognition, identification, and categorization of the stimulus occurs. During this decision process, a many-to-one mapping exists between stimulus and stimulus category (Wickens, 1992) since many stimuli can be recognized as belonging to a single category.

After the stimulus has been perceptually categorized, a decision is made to either take action or place the processed information in storage. Actions may be either

thoughtful or automatic. If no action is required, the information may be stored in short-term or long-term memory.

If action is the decided response, then processing of a chosen *output* response follows. Action feedback may occur so that movement monitoring is possible and adjustments can be made. Feedback may occur through the visual, auditory, tactile, proprioceptive and kinesthetic sensory systems.

Each stage of the input-cognition-output model is assumed to perform some transformation of the stimulus information. It is, therefore, reasonable to assume that each stage requires some finite time to perform that transformation (Wickens, 1992). Traditionally, reaction time has been used to measure the processing time for the input and cognitive stages. Movement time provides a measure of output performance and motor control. Errors, depending on how they are defined, can be a measure of cognitive or motor complexity.

## 1.2 Research Perspective

Human movement can be analyzed within various disciplines. The cognitive psychologist, the biomechanics analyst, and the human factors analyst may approach the same problem from a different perspective. With respect to a choice, hand-to-target aiming task, the psychologist may be interested in the subconscious mental processes involved between stimulus reception and movement initiation. The identification and temporal measurement of each processing stage may then be the approach to modelling stimulus-response behavior.

Within the large framework of human movement exists kinesiology and biomechanics. When studying stimulus-response effects, biomechanics and kinematics of movement must be considered. Kinesiology is the study of body movement while neglecting causative forces and biomechanics is the study of mechanical and physical relationships between body parts employing the laws of physics and concepts form engineering, physiology, and anatomical biology. Kinesiology and biomechanics are concerned with movements that involve flexion, extension, pronation, supination, adduction, abduction, and rotation. Also of importance in these fields are the resultant effects of these movements on body parts under load. Another area of interest is how the limbs may be coordinated with respect to velocities and accelerations in complex movements and how this accomplishes the task at hand. Thus, the biomechanics analyst might be interested in the resultant forces, velocities and accelerations at specific joints. Or, the approach may be to use anthropometric models to explain stimulus-response behavior.

The human factors analyst might be concerned with identifying the particular stimulus display, or type of knob that produced the fastest actuation time, or the color that elicited the quickest or most accurate response. Alternatively, the interest may be to determine optimal control placement. The research reported here followed a behavioral performance approach in which the measurement and modeling of reaction time and movement time were of primary interest.

### 1.3 Application

The importance of reaction time and movement time varies from activity to

activity. For many movements, it is of little significance whether the movement occurs in 400 milliseconds or 4000 milliseconds. Wargo (1967) states that human response limitations have been ignored in the past because they were only critical in a limited number of situations. However, with increasingly sophisticated technologies and increasingly complex human-in-the-loop responsibilities, response time limitations have taken a more central role.

For some movement actions, whether the time to respond to a certain stimulus takes 400 or 4000 milliseconds may be of critical importance. An example is setting flaps to 60 degrees when landing an airplane in a thunderstorm. Whether this action is completed before or after experiencing wind shear may be of critical importance to the crew and passengers. In this case, the critical time difference may not represent a factor of ten as stated above, but rather, may be a response time difference of a few milliseconds.

According to Wargo (1967), the typical total response time to react to a given stimulus and to execute a movement is between 113 and 528 milliseconds which may ostensibly seem insignificant, but may actually be quite critical in certain circumstances. For example, during the peak of his boxing career, Muhammad Ali (a.k.a. Cassius Clay) could execute a 42 cm jab in about 40 milliseconds (Schmidt, 1988). His opponent would, under these circumstances, need a quite rapid response to avoid the blow. And to society, reaction time has obvious importance for such activities as driving an automobile. Here, the difference between a slow and fast reaction to a child darting into the street may have significant consequences.

Identifying those factors that affect human behavior patterns for aimed hand

movements has direct application in designing human-machine systems and their requisite interfaces. Because humans frequently respond to visual and auditory displays and signals, human factors engineers direct a major portion of their research and design efforts toward engineering such systems and their interfaces. An example of a human-machine interface that may be critical in design with respect to temporal performance measures is a helmet-mounted display in a high-performance aircraft. Here, the pilot must detect information displayed on the inside of the visor mounted directly to the helmet and must quickly perform aircraft control movements based on that information. Automobile instrument panels also require relatively accurate, aimed movements in response to stimulus events (e.g., turning on windshield wipers when the view becomes obstructed by rain). Nuclear power plant operations centers and missile launch control centers have long been recognized as requiring critical device control.

### 1.4 Performance Models

It has been shown quite convincingly that human reaction time to a stimulus follows an information-theory based behavioral relationship known as Hick's Law (Hick, 1952). With equal assurance, it has been shown that movement time (following stimulus reaction) behaves according to another information-theory based relationship known as Fitts' Law (Fitts, 1954).

Hick's Law defines human information transmission quantities in bits, where one bit is defined as the amount of information required to reduce choice uncertainty by one-half. When perfect information transmission exists with $n$ equally likely alternatives, the

amount of information conveyed to the observer with each stimulus presentation is given by:

$$H_s = \log_2(n). \tag{1}$$

Hick determined that reaction time (RT) was linearly related to $H_s$:

$$RT = a + b \cdot (H_s), \tag{2}$$

where $a$ is the sum of all delays not associated with decision making, and $b$ is the processing time associated with the doubling of target alternatives (1 bit).

Fitts defined the complexity of a movement as a function of its amplitude (target distance) and required accuracy (target width). Movement complexity, or *index of difficulty* (ID), is given by:

$$ID = \log_2\left(\frac{2A}{W}\right), \tag{3}$$

where $A$ is defined as the movement amplitude and $W$ is the target width. Fitts determined that movement time (MT) was linearly related to ID as follows:

$$MT = c + d(ID), \tag{4}$$

where $c$ is a delay constant depending on the body part making the movement, and $d$ represents the increase in movement time for each additional bit increase in ID.

### 1.5 Bimanual Aimed Movements

The two information-theoretic laws of reaction time and movement time were derived from experimental results that, for the most part, were based on simple one-

handed (*unimanual)* movements toward a single target, or occasionally, one of several targets. The operation or complex devices often involves simultaneous two-handed (*bimanual*) movements. Good examples of systems requiring simultaneous bimanual activity are fixed and rotary wing aircraft, tracked construction vehicles, and automobiles, where operators perform separate and often different movements with each hand.

Bimanual movement has not been extensively studied with respect to Hick's Law and Fitts' Law (Fowler, Duck, Mosher, and Mathieson, 1991). At least two additional facets of movement behavior are involved. The first is the relationship of the two hands moving together to complete a composite task, along with the impact of the second hand on the movement of the first. This involves the comparison of unimanual movement with bimanual movement when both hands are moving to a target of equal difficulty. Second, the study of bimanual movement provides the experimenter the opportunity to examine how two-handed movements of equal difficulty compare to two-handed movements with a task difficulty asymmetry between the hands.

### 1.6 Problem Statement

This research examined bimanual movements within the context of two well-known models of human reaction time and movement time: Hick's Law and Fitts' Law. Specifically, the research was an experimental investigation and characterization of the nature of discrete, choice, stimulus-response movements under the equal-ID and unequal-ID bimanual paradigms. Six main research points were addressed (see Section 6.5 for

a corresponding summary of the results) as follows:

1. Does Hick's Law hold under the bimanual paradigm?

2. Does Fitts' Law hold under the bimanual paradigm?

3. How do bimanual simple reaction tasks and choice reaction tasks differ?

4. How are reaction time and movement time correlated under the bimanual paradigm?

5. Under bimanual conditions, do the limbs act in synchrony?

6. Can bimanual models of bimanual reaction time, movement time, and total response time be derived as a combination of Hick's Law and Fitts' Law?

# CHAPTER II

# LITERATURE REVIEW

## 2.1 Background

The modeling of human stimulus-response characteristics has importance in engineering through identification of those associated human factors that bear directly and significantly on performance and design. Various human movement characterizations can be found in the human factors, ergonomics, motor control, and experimental and cognitive psychology literature.

Schmidt (1988) employed a two-part movement classification scheme. First, he identified tasks as either *discrete*, *continuous*, or *serial*. A discrete task is one that has an identifiable beginning and end. This type of movement is usually fast and is considered cognitive, that is, performed consciously by the subject. On the other hand, a continuous task is one without a discernible beginning and end, such as walking, or steering a car. These tasks usually have long execution times from movement beginning to movement termination and sometimes can be accomplished without conscious subject participation. Common pursuit and compensatory tracking tasks, frequently the subject of human performance experimentation, are of this type. Serial tasks are neither discrete nor continuous tasks but can be considered as a series of discrete movements combined into a continuous activity. An example of this type of task is assembly line work where many discrete sub-tasks are combined to perform a single, larger, seemingly continuous,

super-task. The order of sub-tasks is often important with this activity type.

Schmidt's second classification is between an *open* and *closed dimension* task. An open task is one where the environment continually changes. This changing precludes any pre-planning of responses, except in general terms. The open task necessitates a subject response that is situation specific and usually very fast. Alternatively, the closed task is one where the environment is totally predictable and stable. The subject knows exactly what to expect and can pre-plan responses. Shooting a game of pool is an example of such an activity. The tasks involved in this research were discrete and open in that each movement had a distinct beginning and end and the required movement changed from trial to trial (except under the N = 1 condition).

Human stimulus-response characteristics have been extensively studied (Atha, 1984; Carlton, 1981; Drury, 1975; Fitts and Seeger, 1953; Fitts and Deininger, 1954; Fitts and Peterson, 1964; Fitts and Radford, 1966; Langolf, Chaffin, and Foulke, 1976; Schmidt, 1988). Welford (1980) reports early interest in response time by Bessel in 1820. As an astronomer in Könisberg, Bessel had difficulty resolving data collection inconsistencies between his assistants and himself. They were recording (to the best that current technology allowed) the exact moment certain celestial bodies crossed a hairline in their viewing instruments. To someone predicting the motions of planets and stars, exact timing is critical and the inconsistencies were perturbing Bessel's results.

In 1868, Donders proposed that a series of successive processes or stages occurred between the detection of a stimulus and the subsequent motor response (Bailey, 1982). In 1938, Woodworth (Schmidt, 1988) cited human movement models that Merkel

used in 1885 while demonstrating that response time increases as the number of possible alternatives increases in a choice reaction task. Schmidt (1988) also states that Woodworth published results of his research in movement control in 1899. At that time he suggested that movements begin with an "initial adjustment" that takes the body part near the target and is then followed by a feedback-based "current," or "contemporary control" movement that allows the body part to "home in on the target." This seems very much like the intermittent control model proposed 64 years later by Crossman and Goodeve (1963).

Some of the earliest papers written on the subject of human movement are on the order of 100 years old which means that the problem of human movement has been pondered and studied for quite some time. This period of time notwithstanding, much is still not understood and disagreement exists in the study of human movement (Schmidt, 1988).

## 2.2 Stimulus Response

Response time for any movement response to a stimulus is considered in most of the literature to be made up of at least two distinct elements. These elements are *reaction time* and *movement time* (Welford, 1980; Luce, 1986; Beggs, Graham, Monk, Shaw and Howarth, 1972; and many others). Some researchers include control actuation time in their models since merely moving to a target is often not of any practical significance (Green, 1979; Schlegel, 1989).

Each element represents a delay, or lag in the total movement response to any

given stimulus. Wargo (1967) presents a model of the system of lags and delays in what he calls a *manual control system*. He differentiates between equipment and operator imposed delays. Equipment lags and equipment delays occur in the display of information presented to the operator. Equipment delays can also occur in the target element under control. Operator lags and delays occur in the acquisition and input by receptors of stimuli presented by display equipment. These delays may occur because of afferent and efferent neural activity, in central processing of signals, and in muscle activation. Each delay then represents a limit to the frequency, speed and flexibility of movement that any subject experiences in reacting to stimuli.

Bailey (1982) defines stimulus as "... a physical event, or change in physical energy, that causes physiological activity in a sense organ." Stimuli perceived by a human can vary from electromagnetic energy received by the retina of the eye, to pressure applied to the skin, to alternating compression and rarefaction of air which is perceived as sound. In simple terms, the process of human movement begins with stimulus detection by the human sensory system and ends when the response is completed. The stimulus that generates a human response can be of many forms and may stimulate several sensory systems. Visual, tactile, auditory, and kinesthetic systems all respond to stimuli and may serve as input to movement responses. Within modalities, stimuli can exist anywhere along a dimension continuum along which they are defined. For example, within the visual modality, an electromagnetic stimulus can vary along the frequency, intensity, or duration dimensions. However, some intensities may be below the detection threshold and only certain frequencies are within the visual spectrum.

## 2.3 Information Processing Stages

Three stages of information processing seem to be accepted in modeling human reaction to stimuli. These stages generally correspond to (1) input of stimuli, which is essentially a sensory and perception function, (2) cognition, which involves perception and decision making, and (3) output, which essentially involves the coding and execution of motor responses. It is apparent that these stages overlap with no clear delineation between them. However, various nomenclature and models exist that describe and classify cognitive processing of information from stimulus detection to movement initiation.

Wargo (1967) simply uses *senses*, *central nervous system*, and *skeletal muscular system*. Sternberg (1969) prefers a four-stage model for a binary classification process, but it essentially corresponds to other three-stage models. Sternberg's four stages are *stimulus encoding*, *serial comparison*, *binary decision*, and *translation and response organization*. Bailey (1982) refers to the stages of *perception*, *intellection*, and *movement control*, whereas Schmidt (1988) uses the terms *stimulus identification*, *response selection*, and *response programming*.

Card, Moran, and Newell (1983) have a different approach in characterizing the stages of information processing. They elaborately define the *Human Model Processor* from a memory-model basis. They then divide reaction processes into three interacting subsystems. First, the *perceptual system* transmits and translates external, physical sensations from the environment into "internal representations of the mind." The *cognitive system* is responsible for assigning the correct or optimal response to the

stimulus event. This subsystem integrates the learning experiences and memory of the individual with the retrieval of correlated facts and the appropriate solution algorithms so that the proper response is made and assigned to the *motor system* which then executes the response action.

Based on the above models, it can be said that current cognitive theory of human reaction time assumes the existence of *stages* of processing that must be completed between stimulus detection and response initiation. These stages can be further decomposed into sub-stages. Following stimulus detection, these sub-stages are executed in a serial manner and act *independently* of each other (Bailey, 1982). If the independence assumption is met, then we can simply add the individual stage processing times to determine the total reaction time.

According to Sternberg (1969), Donders proposed that a series of successive processes occur between the detection of a stimulus and the subsequent response. He further theorized that one process begins only when the preceding process is complete.

Donders is generally credited with first proposing this idea and from it he developed what is known as the *subtraction method* for measuring reaction time. The subtraction method compares two, almost identical tasks that require the same processes, or stages, from stimulus to response initiation. The tasks are identical except that an additional element is added to one task. With the additional stage (corresponding to the additional element), the concomitant expansion of its cognitive process set is assumed. The reaction time difference between the two tasks then represents the time required to process the stage associated with the additional element.

Reaction is the link that relates the events of stimulus presentation and physical response action. Luce (1986) calls response time "psychology's ubiquitous dependent variable" because subjects must always react in the experimental setting to some contrivance of the experimenter, and the reaction effect always consumes some measurable amount of time. In general, Luce reasons that if the processing of information by the brain is highly structured, then time differences will exist for different paths through that structure. It is then hypothesized that inferences about the structure are possible by analyzing response time patterns under varying experimental conditions. That is, if the experiment is designed so as to hold time constant for certain processes, then any additional RT can be attributed to some time-lengthening phenomenon for the particular process in question. This is essentially Donders' subtraction method idea from 1868. Luce likens this formidable task to determining the architecture of a computer by measuring its temporal performance when running different software programs.

According to Wargo (1967), a simple reaction typically takes from 70 - 100 milliseconds and a choice reaction typically takes 90 - 300 milliseconds. Wargo, who reviewed the salient literature up to publication in 1967, divides information processing into perceptual and cognitive components. The perceptual processes include *detection*, *identification*, and *recognition* of the stimulus, whereas the cognitive factors include *decision making* and *planning*. He assigns the most significance to the cognitive components in determining reaction time. Typical stage processing times are represented by the following ranges (Wargo, 1967):

1. Sensory receptor 1 - 38 msec

| | |
|---|---|
| 2. Neural transmission to brain | 2 - 100 msec |
| 3. Cognitive processing delays | 70 - 300 msec |
| 4. Neural transmission to muscles | 10 - 20 msec |
| 5. Muscle latency and activation time | 30 - 70 msec. |

Therefore, average reaction time to an unspecified stimulus could be anywhere from 113 - 528 milliseconds. The numbers above reflect the assumptions that the subject is trained and that a cue, or forewarning, occurs before stimulus arrival.

Sternberg (1969) reported a method to determine the presence of information processing "stages" that, in part, determine reaction time. His method tests for additive RT processes without adding or deleting processes to the experimental task as does Donders' subtraction method. Instead, he used what he called the *additive-factor* method to measure interaction effects on RT in varied choice reaction experiments. If interactions are non-zero, then, the stages (as defined by Sternberg) are not additive. Additivity, however does not imply stochastic independence, and Sternberg provides good examples to demonstrate this.

Where Sternberg's additive-factor method differs from Donders' subtraction method is that the additive-factor method does not add or delete stages; it is precisely this adding and deleting that is the weakness in Donders' method because these additions or deletions may affect (interact with) the remaining stages. Systematically, Sternberg alters the experimental task by manipulating the information processed by a stage rather than adding or deleting cognitive processing stages that accompany the task. This method, of course, assumes that the task manipulator has full knowledge of the information

content of each stage.

Sternberg's additive-factor method seeks to find those factors that have additive, non-zero effects, but zero-valued interaction effects. If they exist, then Sternberg deduces that the stages associated with each factor distinctly exist in the reaction process. There are then three ways to determine whether factors are additive: (1) measure deviations from a known linear model, (2) evaluate contrasts or, (3) measure interaction effects. If the stimulus display scanning, signal detection, and response determination stages are independent (i.e., do not interact) then their processing times can be defined by linear functions and are additive.

Different authors have proposed various classifications of the factors that affect reaction time. Bailey (1982) considers reaction time to be dependent on six factors: stimulus type, response required, stimulus detection, stimulus discrimination, cognitive processing, and physical condition of the subject. Welford (1980) divides reaction time into five classes: sensory factors, response characteristics, preparation time, choice, and conscious accompaniments. According to Welford, these five classes were studied by the earliest researchers and he claims them to be relevant and under close study still.

The first class, Sensory Factors, represents the ways in which stimulus information is detected and processed by the subject. Before any particular cognitive process can take place, an interaction between the environment and the subject's sensory system must occur. Given that the stimulus-sensory interaction has occurred, other factors can then be considered. According to Welford (1980), two assumptions are basic to most reaction time models. First, the frequency of sensory impulses generated must be proportional to the stimulus intensity. Second, decision speed varies in relation to the

speed with which these impulses are generated. Welford provides a general model that describes the relation between reaction time and stimulus intensity as used by early researchers:

$$RT = \frac{t}{I^n} + k, \tag{5}$$

where $k$ is an irreducible minimum time for a simple reaction task, $I$ is the measured intensity of the stimulus, $n$ (an empirical constant) is dependent on stimulus condition and the particular sensory organ that is stimulated, and $t$ is a reducible time value. From this relation, it can be seen that as intensity increases, RT will decrease (as long as $n \geq 1$). This relation, however has been found to hold only for moderate intensities because very high intensities may interrupt reaction processes. For example, very loud noise stimuli may actually increase RT by producing startle effects in the subject, whereas very low intensities may fall below the detection threshold.

To complicate matters, not only is reaction time dependent on stimulus intensity but, more accurately, the ratio of the stimulus intensity to the background noise level of that particular stimulus modality. This means that stimulus intensity has a relative effect on RT rather than an absolute effect because of background noise interference. In functional terms, reaction time $RT = f(I/I_0)$, where $I_0$ is a measure of the background noise. In this context, background noise can be considered "neural noise".

Welford (1980) further identifies two other sensory factors that determine reaction time: sensory area ($A$), such as the portion of the tongue particularly sensitive to tasting

salt, and stimulus duration ($t_s$). He also cautions that even though increasing stimulus area or duration generally leads to decreased RT, these changes may in fact lead to slower reaction times because the subject may sample stimulus information longer than is effectively necessary to react. RT can now be thought of functionally as:

$$RT = f(\frac{I}{I_0}, A, t_s). \tag{6}$$

Reaction time also varies with sensory modality. Welford attributes this not to central processing, but rather to differences in "peripheral mechanisms." First, different sensory systems have different afferent transmission rates. Second, the sensory systems do not all change state in reaction to a stimulus in the same way. The example he uses is the difference between the vestibular system that controls subject equilibrium and the auditory system. The vestibular system changes its status much more slowly in response to out-of-balance stimuli than the auditory system responds to noise stimuli. Third, sensory system sensitivity varies. That is, small changes in stimulus intensity for one modality may be discriminated whereas in another modality the same relative change would not. Because of these variations, Welford advises that comparing reaction times across modalities is of little value. Furthermore, he says that no body of evidence exists demonstrating that central processing decision time is consistent across all modalities.

Response Characteristics, Welford's second factor class, identifies physiological conditions acting concurrently with reaction time processes. Here he uses finger tremor, muscle tension and subject respiratory inspiration and expiration as examples. He cites a study in which 75 per cent of the key stokes made by subjects performing a key

depression task occurred on the down phase of a tremor. If true, then the fact that a finger was moving toward the target when the response was initiated is crucial to any temporal analysis.

Welford's third classification, Preparation Time, is the expectancy, or subject preparation for stimulus arrival, which also affects reaction time. Generally, a cue in the form of a warning that the stimulus is about to arrive decreases RT. However, the amount of decrease realized is dependent on the length of the foreperiod, or length of time between the cue and stimulus arrival. It is important to note that the probability of stimulus arrival increases as the elapsed time since the cue was given increases. That is, as time proceeds following the cue, the probability that the signal will arrive in the next instant becomes greater and greater and the subject is increasingly expectant of its arrival. The subject may or may not be conscious of this expectation.

Choice, the fourth classification, refers to the resultant effect from increasing the number of response alternatives or choices. Choice tends to increase reaction time. By increasing the number of target alternatives, the time interval between *like* stimuli increases, thereby reducing the probability that a specific stimulus occurs. It is the probability of occurrence, then, that must affect reaction time. Krinchik (1969) demonstrated the dependence of RT on signal probability regardless of whether the task was simple reaction (1 signal) or choice reaction (2, 4, 8 signals). Figure 2.1 shows how the number of target alternatives can typically influence reaction time.

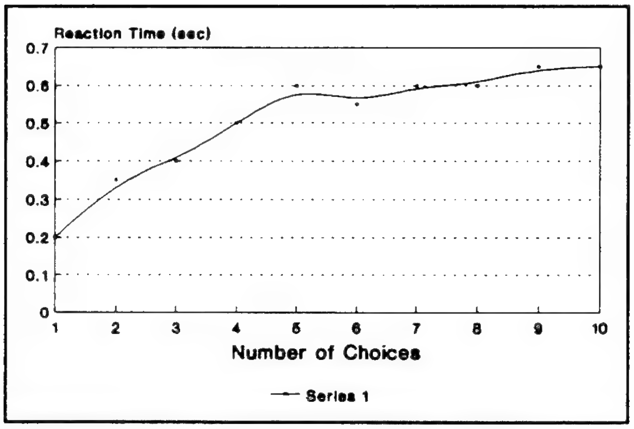


**Figure 2.1.** Choice Reaction Time as a Function of the Number of Choices (Sanders and McCormick, 1987).

If reaction time increases with an increasing number of response alternatives, then, by implication, the additional time required is associated with the response selection stage of information processing (Schmidt, 1988).

Conscious Accompaniment is the final classification identified by Welford. This is simply what the subject is thinking while reacting to stimuli. Conscious accompaniment is difficult to measure and apparently is not examined currently as much as it has been in the past. However, Welford does say that one conscious accompaniment that is still of interest is that of subject confidence when performing reaction tasks. This can be influenced by feedback of subject performance.

Sanders and McCormick (1987) propose the following eight factors as determinants of reaction time:

1. Stimulus modality refers to the domain in which the stimulus resides, such as auditory, visual, tactile, thermal, etc. The auditory modality generally evokes a faster reaction time than the visual modality.

2. Stimulus intensity affects reaction time, with greater intensities generally

evoking shorter response times before showing a leveling off effect at very high intensities.

3. Temporal uncertainty tends to increase reaction time. Conversely, if the subject is provided with some factor that reduces signal uncertainty such as a cue, reaction time decreases.

4. Expectancy is related to temporal uncertainty and reduces reaction time if it exists.

5. Discriminability of the signal affects reaction time because if a signal is easily discriminated, then processing time is reduced and reaction time is decreased.

6. Stimulus-response (S-R) compatibility is negatively correlated with reaction time. If signal and response are highly compatible, then RT decreases. Low compatibility of signal and response results in longer reaction times.

7. Task repetition usually demonstrates a learning effect and results in decreased reaction times.

8. Required accuracy of the movement affects overall RT by reducing stage completion times as accuracy requirements are relaxed. That is, the more accurate the movement must be, the longer it will take to perform.

## 2.4 Performance Model - Reaction Time

As illustrated above, reaction time can be influenced by many factors (Sanders and McCormick, 1987). Probably the most studied factor and the only one for which a "law" has been named is the number of target alternatives, $\boldsymbol{n}$.

Hick (1952) and Hyman (1953), early researchers in reaction time dynamics, relied heavily on the contemporary advances made in information theory as reported by Shannon in 1948. Their seminal work has become the foundation for quantifying reaction time. They concurrently found that for each doubling of stimulus-response alternative choices, subject reaction time increased by approximately 150 milliseconds (Figure 2.1). This insight led them to conclude that reaction time and the number of stimulus-response alternatives were related logarithmically. They also reasoned that the logarithm of the number of alternatives was an indicator of the amount of information that required processing, i.e., the more alternatives present, the more information to be processed.

Hick (1952) was not aware of any literature dealing with the mathematical relationship between RT and the number of possible alternative choices except for one paper by Blank in 1934 who apparently stated without proof or justification that the relationship was logarithmic without proof or justification. Combining the results from Merkel's experiments of 1885 and information theory from Shannon and Weaver (1949), Hick (1952) hypothesized that the rate of gain of information by the human cognitive apparatus, on average, remained constant over time, thus, intimately linking information with reaction time.

Hick borrowed from Shannon and Weaver (1949) the notion that the amount of information contained in an event is given by $-\log(p)$ where $p$ is the probability of occurrence of the signal or event. The negative log is used to always obtain positive values for information content. Information is defined as the amount by which

uncertainty is reduced by the occurrence of an event or the presence of a signal. It is convenient to measure information content or transfer in units of bits. One bit of information is defined as the amount of information required to reduce uncertainty by one-half. Equivalently, it is the information content of a signal, or event that occurs with a probability of 0.5. If the amount of information is calculated as $-\log_2(p)$, then information content measurement units are bits. In this context, it is important to not interpret information as the meaning of the signal, but, rather, as the chance of occurrence of the particular signal out of all other possible signals. This interpretation has proved difficult to comprehend at times. Weaver (1949) offers this explanation,

> "Information . . . is a measure of one's freedom in selecting a message. The greater this freedom of choice, the greater is the uncertainty that the message actually selected is some particular one."

Hick (1952) suggested that the expected or average information $H_{avg}$ contained in a signal is given by:

$$H_{avg} = -\sum_{i=1}^{n} p_i \log_2(p_i), \tag{7}$$

where $p_i$ represents the probability of event $i$.

Hyman (1953) found that RT was inversely proportional to stimulus frequency, or repetition. That is, the more often a particular stimulus occurs, the shorter the reaction time. Reactions were faster for repeated stimuli than for alternated stimuli. Hale (1969) agreed that as stimuli were repeated, RT was shorter compared with alternated stimuli.

In thermodynamics and statistical mechanics, equation (7) is known as an expression of *entropy* and is a measure of uncertainty (Shannon and Weaver, 1949). Entropy is also interpreted as a measure of disorder. Interestingly, information content and disorder represent the same concept. In the context of information content, $H$ represents a measure of the uncertainty surrounding *what* event will occur, which is not the same as the uncertainty that a *particular* event will occur. That uncertainty is given by $-\log(p_i)$ (Hick, 1952).

Hick extended Shannon and Weaver (1949) to the case where the relationship between signal transmitted and signal received is defined. This is a consideration of the case where the signal transmitted is perturbed by noise either in transmission or in receiving, or in the transmission channel itself. If the entropy (information content) of a transmitting source of messages is given by H($x$) and the entropy of the messages at the receiving destination is given by H($y$), then the average information transmitted in the process is given by:

$$R = H(x) - H_y(x) \tag{8}$$

where $R$ is the actual rate of transmission and $H_y(x)$ is a measure of the conditional entropy of $x$ given $y$. Weaver (1949) points out that any uncertainty introduced by the message sender as a result of the freedom to choose from many messages is considered *desirable* uncertainty. However, any noise introduced into the system that reduces the information content of the message is considered *undesirable* uncertainty. The undesirable uncertainty is therefore subtracted from the total to get the useful information

remaining. The amount of undesirable uncertainty, $H_y(x)$, that is subtracted from the entropy of the source $H(x)$ is what Shannon and Weaver call *equivocation*. It refers to the amount of ambiguity that is added to the system by noise.

Wickens (1992) calls equivocation lost stimulus information ($H_L$). This leads to the notion of channel capacity and is interpreted as the rate of useful information that can be transmitted over a channel (Weaver, 1949). If no noise is present on the channel, then $H_y(x)$ is zero and the information transmitted is the information received. In the context of reaction time to a stimulus, an equivocation of zero is equivalent to the subject making no errors in receiving the message. For $n$ equally likely signals or events, the probability of any one signal is $1/n$. From equation (7) and summing over all $i$, with no information loss, the information content is given by:

$$H(x) = -n\frac{1}{n}\log_2(\frac{1}{n}) = \log_2(n) \tag{9}$$

According to Hick (1952), information content is proportional to $\log_2(n) = H_s$ and RT is a linear function of $H_s$. Hick related RT and $H_s$ linearly by:

$$RT = a + b(H_t), \tag{10}$$

where $a$ represents a lower limit in processing time not associated with decision making and $b$ is the processing time associated with the doubling of target alternatives (1 bit). A problem arises when $n = 1$ since $\log_2(1) = 0$ implying that information content is zero. This is not a realistic possibility. To account for this, Hick reasoned that the

subject must decide whether a signal is or is not present in a noise filled environment. Therefore, making this decision is equivalent to adding an additional stimulus alternative to the current state of the S-R ensemble. The modified RT model then expresses reaction time as being proportional to $H_s = \log_2(n+1)$.

Fitts and Seeger (1953) hypothesized that the rate of information transfer depends on stimulus-response (S-R) compatibility, whereas the amount of information transferred does not. Stimulus-response compatibility can be thought of as a "natural" connection or relationship between the stimulus event and its required response. This naturalness has two components. One is the uncertainty the subject feels about a given stimulus-response mapping. The other is related to the experience base of the subject and is a function of what response the subject believes is appropriate for a given stimulus, based on that experience. Fitts and Seeger found that information processing rate was not a function of a particular set of stimuli or a particular set of responses. Rather, they found it to be related to the degree to which the stimuli and responses were congruent. Interestingly, they found that extended training has little effect on S-R compatibility.

Fitts and Deininger (1954) believed, since information processing was essentially a series of processes of decoding and encoding, that RT would be at a minimum if these processes were at a minimum. They tested S-R compatibility as a measure of stimulus and response congruence. Their hypothesis was that for maximum information processing, stimulus and response pairings should correspond to population stereotypes. Their hypothesis was accepted in that significantly better performance was achieved with symbolic coding sets than with spatial coding sets.

Welford (1986), using data from Hale (1969), found that reaction time decreased with training or task practice. Using Hick's model ($RT = a + b\log_2 N$), he found that the value of $a$ (y-intercept) remained constant with practice and that primarily the slope ($b$) changed. This suggests that a minimum bound represented by the constant $a$ exists for response processing. Using a transformation, Welford linked practice effects to reaction performance. Reaction time was regressed on: $RT = A + B\sqrt{T - 1}$ where $T$ is the number of blocks of 200 trials and $A$ and $B$ are the intercept and slope values. The curves generated by the regressions for 2, 4 and 8 target alternatives all reached $a$ (y-intercept) between 6000 and 7000 reactions. That is, it took over 6000 trials before the reactions reached an asymptotic value. Welford says this is much less than the 26,000 reactions reported elsewhere. Either way, the number of reactions for 2, 4 and 8 targets to yield equal RTs is very large.

In summary, reaction time, commonly modeled with Hick's Law, is the resultant sum of cognitive process or stage durations. These stage durations may be a function of stimulus information, stimulus modality, stimulus discriminability, stimulus-response compatibility, movement complexity, and practice (Danev, DeWinter, and Wartna, 1971).

### 2.5 Performance Model - Movement Time

Movement time (MT) is the time taken to physically respond to a stimulus. Timing starts at the exact moment that a body part begins to move following stimulus presentation and ends when the target is contacted. MT is the response duration from

movement initiation to movement termination. It usually does not include the time required to activate a control or manipulate some device at the target position.

Early researchers realized that for any given movement, a speed-accuracy trade-off exists. That is, as the speed of any movement increases (MT decreases), the accuracy of the movement diminishes. This intuitive result was verified experimentally as early as 1899 by Woodworth who found that errors increased with increasing movement amplitude and increasing speed for quick, visually controlled movements (Fitts, 1954).

Fitts (1954) examined the speed-accuracy trade-off of human movement and conducted three seminal experiments to characterize temporal constraints on the human motor system. He is generally credited with making the intellectual leap from the theories of information transfer and channel capacity of electronic communications systems (Shannon and Weaver, 1949) to information transfer and channel capacity of the human motor system. It was the concept of measuring information transfer in bits per second that Fitts applied to the phenomena of human motor control and which became a major cornerstone of motor control theory (Schmidt, 1988).

Fitts (1954) created experimental conditions so that the subject's performance was limited by the capacity of the human motor system. Fitts' first experiment used a reciprocal tapping task where the completion of one movement served as the stimulus for the next movement. All stimulus conditions were held constant except those stimuli that resulted from the subject's own movements. Fitts defined the motor system to include all visual and proprioceptive feedback systems that allow the subject to self-monitor movement.

Fitts believed that there existed a relationship between movement amplitude, movement duration, and target width (accuracy). Specifically, his thesis was that the capacity of the human motor system to process information, for a particular aiming task and for a particular body part, is independent of movement difficulty. That is, speed-accuracy trade-offs occur at a constant information processing rate whether the task is a simple aiming movement or a more complex movement such as placing a ring over a peg. Since the information processing rate is constant, movement time is modulated by the difficulty of the movement as defined by movement amplitude and target width. Fitts sought to unify motor capacity concepts that were lacking in the literature at the time (Fitts, 1954).

Fitts' hypothesis can be restated as: Under task conditions with controlled movement amplitude and target width, and with the subject working at the maximum rate, the average movement time is directly proportional to the average information content per response for those particular task conditions. Fitts believed that a fixed motor information processing capacity accounted for the empirical fact that for quick movements, accuracy decreases with increasing movement amplitude. If true, then this implies that for fixed amplitude and for increasing movement speed, less information can be transmitted in each movement because less time is taken for processing, and movement accuracy decreases accordingly. If movement amplitude increases, then terminal variability and/or movement time increases (Fitts, 1954). Stated another way, when movement difficulty is increased by either increasing movement amplitude or by decreasing allowable movement variance (effective target width), more information is required by the subject to produce a correct movement. Since the maximum rate of

information transmission can not be increased (constant processing), more time is needed to process the additional information. It is this additional processing that results in an increase in movement time (Fitts, 1954; Schmidt, 1988).

Fitts tested his hypothesis by studying subjects performing his reciprocal tapping task as fast as possible while maintaining a low error rate. The task required the subject to hold a stylus in one hand and alternately tap one of two targets located on either side of a home or central position in a horizontal plane. When instructed to begin, the subjects proceeded to alternately strike each target for 15 seconds without stopping, followed by a 55-second rest period between trials. The targets were rectangular metal strips 6 inches long and of four widths -- 0.25, 0.5, 1.0, and 2.0 inches. Four target center-to-center distances between the strips were used -- 2, 4, 8, and 16 inches.

In support of Fitts' hypothesis, movement time increased under two conditions. First, MT increased as target width decreased while holding amplitude constant. Second, MT increased as amplitude increased while holding target width constant. Using the information-theoretic concept of Shannon and Weaver (1949), Fitts proposed that movement time was proportional to the difficulty of the movement. Fitts' Law is given as:

$$MT = c + d \cdot \log_2\left(\frac{2A}{W}\right). \tag{11}$$

Equation (11) implies that movement time is linearly related to $\log_2(2 \cdot A/W)$ which Fitts called the movement *index of difficulty* (ID). The use of $\log_2$ is arbitrary. However, when calculated this way, ID is measured in units of information bits with one bit

equalling the amount of information needed to reduce movement uncertainty by one-half. Fitts' model for task difficulty provides a quantitative way to describe the amount of information necessary to resolve the uncertainty associated with a particular movement. This derivation of movement complexity is similar to the theory of cognitive information processing (Hick, 1952) and human response to alternative target choices.

Notice that ID remains constant if the ratio of $2 \cdot A/W$ remains constant. This is an important finding which says that no matter how the task difficulty is constructed through manipulation of target size and position, MT is *only* a function of the ratio of movement amplitude and target width. If the ratio remains constant (e.g., by doubling target distance and width simultaneously), then predicted MT remains constant. Fitts multiplied the amplitude in the numerator by 2 so that the possibility of negative values of ID were eliminated. He also reasoned that a 2 was necessary because the subject had to choose a movement that could overshoot or undershoot the target (Welford, 1960).

In equation (11), $c$ and $d$ are empirical constants which depend on the task and the involved body part. The value of $c$ represents the theoretical movement time if task difficulty is zero. This occurs when $2A = W$ so that $\log_2(2A/W) = 0$. This is a curious case of the left and right targets touching (Schmidt, 1988). The non-zero y-intercept is generally believed to represent the amount of movement time required for very small Ids. As ID becomes smaller, MT approaches a constant value. Fitts' Law tends to under predict MT at low ID values (Wickens, 1992). MacKenzie (1989) agrees that Fitts' Law does, in fact, fail when ID is small.

The empirical constant $d$ is the value of the slope of the line defined by (11) and

represents the increase in MT for a unit increase in ID. Schmidt (1988) describes it as the sensitivity that the body part in question shows in response to a unit increase in ID. See Langolf, Chaffin, and Foulke (1976) for a graphical depiction of how movement time slope changes with arm, wrist and finger movements. The rates for the appendages were 38 bits/sec, 23 bits/sec and 10 bits/sec respectively.

MacKenzie (1989) points out that Shannon's original equation defining channel capacity was given by:

$$C = B \cdot \log_2\left(\frac{P+N}{N}\right). \tag{12}$$

where $P$ is the signal power and $N$ is the white noise level of a communication channel. The analogy to Fitts' Law would yield:

$$MT = c + d \cdot \log_2\left(\frac{A+W}{W}\right). \tag{13}$$

According to Welford (1960), a better fit is obtained by using a compromise function:

$$MT = c + d \cdot \log_2\left(\frac{A+0.5W}{W}\right) = c + d \cdot \log_2\left(\frac{A}{W}+0.5\right). \tag{14}$$

Welford points out that this can be interpreted as a kind of Weber fraction where the subject must distinguish between the far and near edges of the target. Also, since the logarithm of the ratio of $(A+0.5)/W$ will never be negative, the multiplication of $A$ by 2 is unnecessary as suggested by Fitts. MacKenzie (1989) compared fitted data using Fitts', Welford's and Shannon's models and found the best fit was given by the Shannon model, followed by Welford and Fitts.

## 2.6 RT-MT Relationships

The degree to which reaction time and movement time are related has been studied and the results seem mixed. Some evidence exists for a positive RT-MT correlation, whereas the reverse conclusion of independence has also been drawn. It seems intuitive that as movement accuracy requirements increase, more information must be processed to account for the increased difficulty. It is reasonable to conclude that any additional information processing would require additional reaction time to execute the movement unless the additional processing takes place after the movement is initiated.

Beggs, Graham, Monk, Shaw and Howarth (1972) pondered whether Hick's Law and Fitts' Law can be combined to produce a model of total response time as a linear combination of RT and MT. Since both laws are based on information-theoretic principles, they reasoned that a simple "fusion" of the laws into a single equation relating speed and accuracy of human reaction and movement should be possible. The existence of a single equation relating these two phenomena assumes that information is processed serially, and that parallel processing does not occur.

The equation used by Beggs et al. (1972) was a simple addition of the equations from Fitts (1954) and Hick (1952) given by:

$$t_T = (a + c) + b\log_2\left(\frac{A}{W} + 0.5\right) + d\log_2 n. \tag{15}$$

The values of ***a, b, c*** and ***d*** are empirical constants that are situation specific and are dependent on the body segment that moves as stated earlier. Notice that Beggs et al. (1972) used the suggestion of Welford (1968) for computing the index of difficulty, and

used $n$ instead of $n + 1$ for the number of alternatives in the reaction time portion of the model.

To test the prediction of response time based on the model in equation (15), Beggs et al. designed an experiment in which subjects responded to pea bulb type stimuli by striking a graph paper target with a pencil. Between trials the experimenters varied the number of targets (either 1, 2, 4, or 8). Unlike Fitts' experimental tasks, however, Beggs et al. (1972) did not measure time as their dependent variable. Instead, they paced the movement speed of each subject and measured the error variance as the dependent variable. Accuracy was measured as the root mean square (RMS) error of pencil marks distributed around the target line on the graph paper. Target amplitude was held constant at 500 millimeters. To pace each subject's movement, a metronome was used with rates of 60, 75, 85, 100, 120, 133, 150, and 171 beats per minute. This resulted in movement times ranging from 350 to 1000 milliseconds.

Based on the experimental data and results from ANOVA and regression analyses, the authors concluded that the number of target alterative affects the speed-accuracy trade-off relationship by increasing MT. That is, providing target alternatives affects the channel capacity of the information processing system resulting in a violation of the assumption of serial information processing. Therefore, MT and RT are not independent since each is a function of the number of target alternatives.

Beggs et al. (1972) used an equivalent target width $w'$ instead of the actual target width. This equivalent width contained 96 percent of the movement hits made by the subject on the target graph paper. The model they used was:

$$\log_2(\frac{A}{w'} + 0.5). \tag{16}$$

Based on this model and the experimental data, they found y-intercept values ($a + c$) that were negative and declared this result to be "nonsense." However, other authors have arrived at similar y-intercepts and have not classified them as such (MacKenzie, 1989; Fitts, 1954; Welford, 1968; Brogmus, 1991). Beggs et al. (1972) also found MT to be a function of the number of target alternatives which violates the independence of RT and MT. If RT and MT are not independent, they cannot be added as a simple linear combination. Beggs et al. (1972) found less support for Fitts' Law than for Hick's Law. Since the serial processing assumption (independence of RT and MT) on which they based their hypothesis was violated, their fusion of Hick's and Fitts' Laws was, therefore, ruled invalid. If MT and RT cannot be added in a linear sense, then this implies that they are related measures and an overlapping of mental processes may occur. That is, parallel processing occurs either exclusively or in some combination of serial-parallel processing to execute a response to a stimulus.

Using an intermittent correction hypothesis, Howarth, Beggs and Bowden (1971) developed an alternative to Fitts' movement time model. Accuracy was predicted as a function of the amplitude of the last intermittent correction, which in turn varies with the speed of the movement. This model, applied by Beggs et al. (1972) to the data described above, is given by:

$$E^2 = E_0^2 + k^2\sigma_\theta^2 t_\mu^{2.8} T^{-2.8}. \tag{17}$$

$E^2$ is the on-target error, $E_0^2$ is tremor error, $k$ is a constant and a function of the

trajectory length, $\sigma_\theta$ is the aiming angular velocity, $t_\mu$ is the corrective reaction time, and $T$ is the movement time. These data did support the intermittent correction model of movement. However, it must be noted that Beggs et al. (1972) did not use the same dependent variable as Fitts. They used accuracy (RMS error) instead of MT as originally used by Fitts (1954). Therefore, the difficulty in generalizing these results to an information-theoretic combination of Hick's Law and Fitts' Law was not surprising.

Schmidt (1988) reports criticisms of the intermittent correction hypothesis by pointing out that the model applies to situations where humans have sufficient information processing time to be useful in rapid movements. Even if a single correction can be made within a few hundred milliseconds (typical rapid movement time), it is doubtful that there exists enough time for a second or third correction. Biomechanical analysis also exposes this weakness. Langolf, Chaffin, and Foulke (1976) reported that most movements they studied had only one correction, and some had none. The intermittent corrections theory is also questioned by Fowler, Duck, Mosher, and Mathieson (1991) and by Marteniuk, MacKenzie, and Baba (1984).

Groves (1973) filmed 16 college student-athletes in a swimming race start. Reaction time and movement time were measured separately. RT began when the starter's pistol fired and ended at the first sign of the subject's movement. MT began when RT stopped and ended when the subject's feet left the starting blocks. The events were filmed at 60 frames per second. Experimental results indicated an RT-MT Pearson-product moment correlation of -0.231 ($p > 0.05$). The coefficient of determination, $\mathbf{R}^2$, was 0.053. Thus, only 5 per cent of the variation in RT was associated with variation

in MT. From this, Groves concluded that RT and MT are independent factors in the movements produced by the gross motor skills tested under these particular conditions.

If movement time and reaction time are governed by some common underlying mechanism, then RT-MT correlation should be high. In response to reports that such was the case, Henry (1961) conducted an experiment where subjects moved their laterally stretched arms forward 90 degrees to hit a target when an auditory stimulus occurred. Subjects were instructed to swing their arms as rapidly as possible. For 120 subjects performing this task, the RT-MT correlation was 0.02. Analysis of variance of regression also excluded any non-linearity as a cause of the low correlation between RT and MT. Again, this result suggests that reaction time and movement time are independent factors.

Danev, DeWinter, and Wartna (1971) studied the relationship between RT and MT by focusing on task performance instead of task structure. Examples of task structure include such factors as stimulus information, stimulus modality, stimulus discriminability, S-R compatibility, and practice. In contrast, Danev et al. (1971) examined the RT-MT relationship as a function of a factor that is task performance related (e.g., the time available to organize a response).

Danev et al. (1971) studied the RT-MT relationship under three hypotheses. The first hypothesis, under conditions of a choice reaction task, stated that a subject's RT and MT will either be positively related or independent if the subject is given sufficient time to correctly organize a response. This hypothesis is based on the assumption that when the allowed total response time is long, the subject's vigilance to respond will be low with an equally strong influence on RT and MT. The second hypothesis stated that RT

and MT will be inversely related if the total allowed time to respond is shortened to effectively stress the subject, while maintaining the motivation to be error free. Danev et al. (1971) based this hypothesis on the assumption that the subject will be able to compensate for a long reaction time with a short movement time. Their third hypothesis stated that subjects are able to estimate the RT in relation to the total response time. The subject then initiates a complex motor movement with long MT if the RT is short, and initiates a simple motor movement with short MT if the RT is long.

Two separate experiments were conducted by Danev et al. (1971) to test the three hypotheses. The first experiment was conducted under two conditions that differed only in the time allowed to respond. The time allowed to respond in the second condition was one-fourth the time allowed in the first condition. The second experiment sought to determine whether subjects could consciously contribute to changing an RT-MT relationship by modifying their movements.

Using *t*-tests, both the non-stressed and stressed conditions were shown to have significant differences in their MTs associated with the 10 shortest and 10 longest Rts. In the stressed condition, significantly shorter Mts were associated with longer Rts, whereas in the non-stressed condition, longer Mts were associated with longer Rts. These results supported the first two hypotheses. Danev et al. (1971) concluded that with no time stress, RT and MT are directly proportional. Under time stress conditions RT and MT are inversely proportional, and subjects can estimate RT and adapt their MT to it.

Several other authors support the independence of RT and MT based on research

that results in low correlations, apparently not significantly different from zero. Mendryk (1960) reported $r$ values of 0.127 for short movements and 0.138 for long moments when studying RT-MT relationships for three age groups with means of 12, 22 and 48 years. Smith (1961) reported correlation coefficients for the RT-MT relationship of -0.06 and 0.23 when studying discrete arm-swing movements. Lotter (1960) tested 105 college-aged men for arm and leg RT-MT correlations and found essentially none significantly different from zero. Even though one right arm RT-MT correlation was found to be significantly different from zero ($r = -0.208$, $p = 0.05$), Lotter argued that "There is very thin evidence of other than zero correlation between RT and MT in these data."

Kerr (1966), on the other hand, when studying RT-MT relationships in 47 male college students performing a knee extension task found RT-MT correlations to be much higher. In fact, they were positively correlated with $r = 0.538$ and $r = 0.629$ for two identical tests conducted a week apart. These correlation coefficients were found to be significantly different from zero at $\alpha = 0.01$.

### 2.7 The Bimanual Task

Up to this point in the literature review, the reported experiments have all been based on one-handed or *unimanual* stimulus-response aiming tasks. However, the movements performed by humans (and all animals) often involve separate and simultaneous action of various limbs. In what fashion are these movements coordinated to achieve a single goal? What are the processes that underlie the total combined

movement of limbs when they move simultaneously? What relationships exist when the limbs are moving together but under different spatial constraints in which the difficulty level of one limb differs from that of another?

Peterson (1965) suggested that performance differences between contralateral limbs in two-handed movements are attributable to Response-Response (R-R) compatibility effects. Where Stimulus-Response (S-R) compatibility associates performance with the naturalness between stimulus and response, R-R compatibility associates performance with the naturalness between concurrent motor responses. According to Fitts (1959),

> "Response-response (R-R) compatibility effects arise whenever two or more separate response processes are carried on concurrently, such as when an individual sings and plays his own piano accompaniment, or when an individual operates aircraft flight controls with his right hand and adjusts engine controls with his left hand."

Peterson (1965) tested R-R effects under the bimanual paradigm. He found that R-R effects are evident when significant interaction effects exist as opposed to significant main effects. He tested three subjects performing left and right unimanual and bimanual aiming tasks under all direction conditions of distal, proximal, medial, and lateral movement. Peterson found few RT differences between conditions, except that unimanual Rts were shorter and that any conditions involving distal movements took longer. He reported no statistically significant effects. No appreciable RT-MT correlation was obtained. The highest error percentage occurred under the condition of one hand moving distally while the other hand moved laterally (high degree of spatial asymmetry). The least errors occurred for one-handed movements.

For the unimanual tasks, Peterson found no significant hand effect. The direction of movement, however, did have a significant effect, $F(2,96) = 8.2$, $p = 0.05$. For both hands, lateral motions were the fastest and the proximal movements the slowest.

For two-handed, bimanual movements also, lateral motions were fastest and proximal motions were slowest. Hands did not significantly differ. However, the left-right interaction was significant, $F(9,191) = 12.0$, $p = 0.01$. According to Peterson, this interaction implies a significant R-R compatibility effect. When concurrent motor responses occur, the performance level of one hand is dependent on the nature of the response of the other hand. That is, task complexity of the opposite hand significantly affects performance and is evident by the presence of significant interaction effects.

Kelso, Southard, and Goodman (1979) conducted three experiments to study the issues of bimanual movement. They noted that little research had been reported on the principles of coordinated inter-limb movement. From their research they suggested a *coordinative structure* model.

Kelso et al. (1979) defined a coordinative structure as a functional grouping of muscles that are constrained to act as a single unit. What they sought to determine was whether the limbs, in a bimanual task, are controlled separately when the hands are moving to targets of differing Fitts indices of difficulty, or are constrained to act as a single unit. The answer would shed light on whether "central commands," or process stages, detail each movement for each hand separately, or whether central commands are issued to functional groupings of muscles. These functional groups would then act as a biomechanical unit (coordinative structure) where the movements are carried out

autonomously and simultaneously.

To gain insight into this problem, Kelso et al. (1979) tested twelve subjects performing bimanual movements where two limbs moved toward targets of differing indices of difficulty based on one auditory stimulus. That is, one hand moved to an "easy" target while another moved to a "hard" target.

Kelso et al. (1979) used the same apparatus in three separate experiments that required the subjects to perform different tasks, with each task based on different spatial and biomechanical direction of movement considerations. In the first experiment, subjects moved from home positions forward of their frontal plane, near the midline of their bodies, to lateral positions extending to either side of the mid-sagittal plane. These movements essentially involved only elbow extension when moving to the target and flexion when returning to the home position. To test movement in the opposite direction, subjects in the second experiment moved from lateral positions that served as the targets in the first experiment to targets that were initially the home positions. This home-target reversal was tested to determine whether having the target in peripheral or primary vision affected performance (it did not). Since the first two experiments involved movements of the two arms in opposite directions, a third experiment was conducted to test performance of bimanual movement in the same direction. Here subjects moved in the sagittal plane from home positions located near their body midline to targets directly in front of the home positions.

Tables 2.1 through 2.3 present the RT and MT means from the three experiments. Kelso et al. (1979) found in all three experiments that no significant RT differences occurred between the hands ($p > 0.05$). Unimanual and bimanual equal-ID movement

times in the first experiment were not significantly different ($p > 0.05$). However, movement times to the easier of the two targets were significantly longer in the bimanual unequal-ID task when compared to the bimanual equal-ID task and the unimanual task ($p = 0.01$).

Kelso et al. concluded that the difficult task determined the movement time in the two-handed condition. Interestingly, they also found that movements were terminated simultaneously. They suggested that the hand moving to the less difficult target played a subsidiary role while the subject paid more attention to the more difficult movement.

Table 2.1. Results from Kelso et al. (1979) - Lateral Movement.

| | **HAND** | | | |
|---|---|---|---|---|
| | **LEFT** | | **RIGHT** | |
| **ID** | **RT** | **MT** | **RT** | **MT** |
| **UNIMANUAL** | | | | |
| 0.74 | 205 | 82 | 218 | 78 |
| 3.73 | 220 | 151 | 218 | 159 |
| **BIMANUAL EQUAL-ID** | | | | |
| 0.74 | 219 | 89 | 224 | 85 |
| 3.73 | 237 | 166 | 240 | 169 |
| **BIMANUAL UNEQUAL-ID** | | | | |
| 3.73/0.74 | 238 | 155 | 246 | 133 |
| 0.74/3.73 | 243 | 140 | 240 | 158 |

Table 2.2. Results from Kelso et al. (1979) - Medial Movement.

| | **HAND** | | | |
|---|---|---|---|---|
| | **LEFT** | | **RIGHT** | |
| **ID** | **RT** | **MT** | **RT** | **MT** |
| **UNIMANUAL** | | | | |
| 0.74 | 229 | 140 | 228 | 140 |
| 3.73 | 224 | 221 | 231 | 218 |
| **BIMANUAL EQUAL-ID** | | | | |
| 0.74 | 235 | 150 | 243 | 145 |
| 3.73 | 232 | 216 | 237 | 220 |
| **BIMANUAL UNEQUAL-ID** | | | | |
| 3.73/0.74 | 238 | 213 | 253 | 192 |
| 0.74/3.73 | 244 | 183 | 238 | 209 |

Table 2.3. Results from Kelso et al. (1979) - Distal Movement.

| | **HAND** | | | |
|---|---|---|---|---|
| | **LEFT** | | **RIGHT** | |
| **ID** | **RT** | **MT** | **RT** | **MT** |
| **UNIMANUAL** | | | | |
| 0.74 | 196 | 95 | 194 | 101 |
| 3.73 | 204 | 142 | 202 | 147 |
| **BIMANUAL EQUAL-ID** | | | | |
| 0.74 | 205 | 106 | 209 | 103 |
| 3.73 | 216 | 147 | 220 | 146 |
| **BIMANUAL UNEQUAL-ID** | | | | |
| 3.73/0.74 | 218 | 154 | 231 | 130 |
| 0.74/3.73 | 214 | 129 | 217 | 143 |

The bimanual MT results could not be attributed to primary/peripheral vision differences. Results from all three experiments suggested that a simultaneity of actions (both reaction and movement) occurred in the bimanual movement which supported their coordinative structure mechanism as a model of the two-handed movement to a target.

The biomechanical analysis of high-speed photogrammetric data from Kelso et al. (1979) also supported the coordinative structure model in that results showed a virtual synchronization of limbs with respect to velocity and acceleration peaks associated with the limbs leaving the home positions simultaneously and reaching their respective targets simultaneously. This, too, supported the coordinative structure model by suggesting an interaction of the limbs that would not be consistent with independent programming of separate movements.

Kelso, Putnam, and Goodman (1983) further pursued evidence for the coordinative structure model. They placed an obstacle in the path of one limb to create asymmetric task difficulty between the hands. The findings supported their hypothesis that the limbs co-ordinate as a unitary structure. They extended the coordinative structure concept to include an element in the model of the limbs behaving qualitatively as a "non-linear oscillator."

An entirely different finding and interpretation of the violation of Fitts' Law are proposed by Marteniuk, MacKenzie, and Baba (1984). In no uncertain terms, Marteniuk et al. (1984) rejected the conclusions and model of Kelso et al. (1979, 1983). Using their own data and also the data of Kelso's group, they, too, found that Fitts' Law was violated in the bimanual, unequal-ID aiming paradigm. Marteniuk et al. (1984) proposed that the behavior can better be represented with a neurophysiological *cross-talk* model.

In this model, commands from the central nervous system are propagated along efferent contralateral and ipsilateral descending pathways or "streams." In this case, cross-talk occurs between streams where unintended signals may be propagated, thus producing interference. It is this interference over the neural pathways that accounts for the resultant timing differences that are observed.

Marteniuk et al. (1984) tested 10 subjects moving styli either 10 centimeters or 30 centimeters to a one millimeter target. Each subject completed eight experimental conditions (four unimanual and four bimanual) with 20 trials per condition. Table 2.4 lists the mean Rts and Mts from the experiment.

Table 2.4. Results from Marteniuk et al. (1984).

| | **HAND** | | | |
|---|---|---|---|---|
| | **LEFT** | | **RIGHT** | |
| **ID** | **RT** | **MT** | **RT** | **MT** |
| **UNIMANUAL** | | | | |
| 7.64 | 247 | 238 | 242 | 238 |
| 9.22 | 256 | 307 | 251 | 295 |
| **BIMANUAL EQUAL-ID** | | | | |
| 7.64 | 256 | 233 | 259 | 235 |
| 9.22 | 263 | 282 | 267 | 281 |
| **BIMANUAL UNEQUAL-ID** | | | | |
| 7.64/9.22 | 255 | 272 | 254 | 293 |
| 9.22/7.64 | 253 | 285 | 261 | 250 |

Reaction time analysis comparing unimanual vs. bimanual equal-ID conditions found that unimanual RTs were faster (249 vs. 261), $F(1,9) = 9.85$, $p = 0.05$. RTs

were significantly longer for the ID = 9.22 targets, $F(1,9) = 5.42$, $p = 0.05$. There was no significant hand effect, nor significant hand interactions.

Regarding movement time, ID was significant with the harder targets requiring longer movement times, $F(1,9) = 41.37$, $p \leq 0.05$. There was no significant interaction of hand and unimanual-bimanual condition. That is, the left hand/right hand MT performance difference was the same under the unimanual and bimanual equal-ID conditions.

RT analysis comparing the bimanual equal-ID vs. bimanual unequal-ID conditions identified a significant DISTANCE x HAND interaction, $F(3,27) = 5.3$, $p = 0.05$. Post-hoc analysis showed that for both hands, RT to the ID = 9.22 target was longer when the other hand also moved to the ID = 9.22 target than when the other hand moved to the ID = 7.64 target. In the 9.22/7.64 condition, the left hand RT was shorter than the right hand RT. That is, the hands were not synchronized in leaving the home positions.

MT analysis of the bimanual equal-ID vs. bimanual unequal-ID conditions also indicated a significant DISTANCE x HAND interaction, $F(3,27) = 29.73$, $p \leq 0.05$. Post-hoc analysis showed that for both hands, MT to the ID = 7.64 (easy) target was shorter when the other hand was also moving to an ID = 7.64 target than when the other hand was moving to the difficult target. Also, for the right hand only (ID = 9.22), MT was longer for the 7.64/9.22 condition than for the 9.22/9.22 condition. The hand moving to the 7.64 target (left and right) was faster than the hand moving to the 9.22 target.

Knowing that Fitts' Law is violated in bimanual aiming tasks under asymmetric conditions, Fowler et al. (1991) investigated the appropriateness of the coordinative structures and neural cross-talk models. They collected RT, MT, and kinematic data for a bimanual, unequal-ID aiming task. The task was the two-handed analogue of the unimanual simple reaction task. That is, subjects aimed at and struck one target with each hand when the appropriate stimulus was detected.

Fowler et al. (1991) used 12 right-handed subjects between 18 and 23 years. The target apparatus was a table top target surface where two spring-loaded, normally closed, telegraph keys were mounted. Relaxation and depression of the keys opened and closed a circuit. The home positions were located 8.5 cm apart. Two interchangeable metal targets were located in line with each home position. This line was perpendicular to the table edge and the subject's frontal plane. Three ID levels were tested (0.77, 3.73, and 5.17). The first two IDs were those used by Kelso et al. (1979, 1983). A tone generator was used to provide the movement stimulus. After receiving the stimulus, the subject was to move the appropriate hand(s) toward the appropriate target(s). Separate timers were used to measure RT and MT. Errors were measured by the timers continuing to run until a target was successfully touched. Kinematic data were collected using the Waterloo Spatial Motion Analysis and Recording Technique (WATSMART) system.

Each subject performed under thirteen conditions that were divided into three hand-target categories: (1) six unimanual tasks, three left and three right unimanual, one at each of the three ID levels; (2) three bimanual equal-ID tasks, one at each of the three ID levels; and (3) four bimanual unequal-ID tasks. Under the bimanual, unequal-ID condition, four ID left/ID right target combinations were used (0.77/3.73, 3.73/0.77,

0.77/5.17 and 5.17/0.77). A variable foreperiod was provided to cue the subject that a stimulus was about to arrive. Each subject received five familiarization trials before performing 15 data trials. A trial was repeated if it did not satisfy the following criteria: (1) a target was hit without error, (2) RT was between 90 and 600 milliseconds, and (3) MT was between 30 and 600 milliseconds. Fowler et al. did not offer justification for these criteria. However, they were the same as those used by Kelso et al. (1979). Table 2.5 presents the mean RT and MT results. The number of errors increased with increasing task difficulty.

To analyze RT performance under the unimanual and bimanual equal-ID conditions, a 2 x 2 x 3 repeated measures ANOVA (CONDITION x HAND x ID) was conducted. Two main effects were significant: CONDITION (unimanual or bimanual equal-ID), $F(1,11) = 39.54$, $p \leq 0.001$, and ID, $F(2,22) = 19.70$, $p \leq 0.001$. That is, RTs for the unimanual task were shorter than RTs for the bimanual equal-ID task, and harder tasks had longer RTs than easy tasks. There was no significant hand effect. This suggests that a synchrony between hands existed in reaction behavior for the unimanual and bimanual equal-ID condition. RT and MT were positively correlated.

Examining the bimanual unequal-ID condition data separately, 2 x 2 x 2 ANOVAs (HAND x ID) were conducted with the following results. A significant HAND x ID interaction for the 0.77/3.73 ID pair occurred, $F(1,11) = 8.56$, $p = 0.01$. This means that the hands performed differently under different ID conditions. However, only 2 milliseconds separates the hands for the 0.77/3.73 ID pair (301 vs. 299) while 10 milliseconds separates the hands for the 3.73/0.77 ID pair (293 vs. 303). No significant

interaction effects for the 0.77/5.17 ID pair were found. Regardless of the hand target difficulty, RT performance was not significantly different. Therefore, the authors concluded that the two hands had the same RT under the bimanual equal-ID and the bimanual unequal-ID conditions.

Table 2.5. Mean RT and MT results from Fowler et al. (1991).

| | HAND | | | |
|---|---|---|---|---|
| | LEFT | | RIGHT | |
| **ID** | **RT** | **MT** | **RT** | **MT** |
| **UNIMANUAL** | | | | |
| 0.77 | 281 | 102 | 276 | 92 |
| 3.73 | 291 | 185 | 289 | 170 |
| 5.17 | 298 | 237 | 307 | 232 |
| **BIMANUAL EQUAL-ID** | | | | |
| 0.77 | 289 | 108 | 288 | 106 |
| 3.73 | 300 | 196 | 306 | 192 |
| 5.17 | 319 | 252 | 324 | 242 |
| **BIMANUAL UNEQUAL-ID** | | | | |
| 0.77/3.73 | 301 | 148 | 299 | 177 |
| 3.73/0.77 | 293 | 189 | 303 | 151 |
| 0.77/5.17 | 301 | 174 | 297 | 222 |
| 5.17/0.77 | 312 | 262 | 310 | 196 |

For MT, the unimanual and bimanual equal-ID data were analyzed together in a 2 x 2 x 3 repeated measures ANOVA (CONDITIONS x HAND x ID). The following main effects were significant: HAND, $F(1,11) = 9.58$, $p = 0.01$ (the left hand was

slower than the right - 180 vs. 172 msec); CONDITION, $F(1,11) = 9.04$, $p = 0.01$ (two hands were slower than one - 182 vs. 169 msec); ID, $F(2,22) = 326.25$, $p = 0.0001$ (MT increased with increasing ID - 102 vs. 185 vs. 240 msec).

To determine where Fitts' Law was violated, three different analyses were performed on the bimanual unequal-ID data. Each bimanual unequal-ID condition was compared separately against its bimanual equal-ID counterpart in a 3 x 2 repeated measures ANOVA (CONDITION x HAND). Each hand's performance under the equal-ID pair conditions was compared against the same hand's performance under the unequal-ID conditions. For example, the left hand MT under the 0.77/0.77 condition was compared against the left hand MT under the 0.77/3.73 and 0.77/5.17 conditions. The left hand MT under the 3.73/3.73 condition was compared against the 3.73/5.17 condition. The same analyses were performed for the right hand. A significant condition effect was found for the ID = 0.77 (easy) target, $F(2,22) = 78.07$, $p = 0.001$. Contrasts showed that the hand moving to the easy target slowed as the contralateral limb was tasked with increasing difficulty. No similar effects were found for separate analyses on the ID = 3.73 and ID = 5.17 targets.

From the above results, Fowler et al. (1991) concluded that Fitts' Law is violated only when moving to the lower ID target in the bimanual unequal-ID condition. This is the same conclusion reached by Kelso et al. (1979, 1983) and by Marteniuk et al. (1984). Analysis of timing differences between the hands for the bimanual equal-ID and bimanual unequal-ID tasks revealed that for equal-ID conditions, MTs did not differ between hands. However, the largest MT difference between hands for the equal-ID condition

(10 msec) differed significantly from the smallest MT difference between hands for the unequal-ID condition (34 msec). The smallest MT difference between hands with unequal-IDs (34 msec) differed significantly from the largest MT difference with unequal-IDs (57 msec). Thus, hand movement timing differed and was positively correlated to the difference in ID between target pairs.

Kinematic analysis showed that, with the exception of one subject who maintained synchronization throughout all conditions, the subjects revealed a wide range of MT desynchronization in the unequal-ID conditions. For the equal-ID conditions, synchronization of the limbs was maintained for the group of subjects as a whole.

The most telling feature of the plotted MT kinematic data was that for the unequal-ID conditions, the first acceleration peaks were synchronized but the last peaks, representing the beginning of the deceleration to the target, were not. Consistently, across all subjects, the hand targeted at the 0.77 ID target arrived first. Analysis of the time differences between the first and last acceleration peaks was conducted. Adjustments were made to allow for RT differences between hands. However, it could not be demonstrated that RT differences between the hands affected the kinematic synchronization of the two limbs. It was concluded that as the ID difference between targets increased, a progressive decrease in MT synchronization of the last acceleration peaks occurred.

Even though no evidence was found to conclude that RT differences did influence the synchronization of the hands in moving as a unit, Fowler et al. (1991) stated that the negative result is not strong enough to conclude that such a possibility does not exist.

To summarize, Fowler et al. (1991) found that (1) RT increased with the use of

an additional hand, (2) RT increased as ID increased, (3) RT increased when the task difficulty was asymmetric, (4) RT for the two hands was virtually identical, (5) MT for the hand that moves to the easier target under the unequal-ID condition was longer than the corresponding MT for the bimanual equal-ID case, while MT for the other hand did not change, (6) MT differences existed between hands and varied as a function of ID differences and total MT, and (7) large variations in limb synchronization existed between subjects.

In answer to the question of which model, the coordinative structure model (Kelso et al., 1979, 1983) or the neural cross-talk model (Marteniuk et al., 1984) better fits reality, Fowler et al. (1991) stated that neither model was adequate to completely represent the behaviors noted. The authors did however, conclude that the linear coordinative structure model is invalid because of the desynchronization between limbs that was noted and found to be significant. The fact that the initial movements of the limbs were synchronized supported both models. The large timing differences between the hands supported the Marteniuk model. Both models predicted that the difficult-ID hand should also be affected. Both failed in this regard. Fowler et al. (1991) suggested that vision may be a factor overlooked by each model and this additional factor needs more study.

In order to make a contribution to this enormous body of literature, a series of experiments was conducted to test bimanual limb synchrony and the temporal performance effects of asymmetric hand tasking. Based on the existing literature, this dissertation sought to better understand subject behavior and performance under the bimanual aiming task paradigm compared with the unimanual aiming task. In order to

do this, the task requirement of the contralateral limb, or complimentary hand, was examined. This was necessary because the nature of the bimanual task is made unique by tasking an additional limb for simultaneous performance activity. Indeed, it is this additional tasking that creates differences in performance between the unimanual and bimanual tasks.

For this task distinction, the notion of ***opposite-ID*** was used to specifically refer to the task difficulty for the opposite hand. It is the existence of a task requirement for the contralateral or opposite limb, that makes the bimanual aiming task more than a simple extension of the Hick-Fitts model.

# CHAPTER III

## PILOT STUDY I

### 3.1 Purpose

Pilot Study I was conducted at the University of Oklahoma, Norman, Oklahoma in the Information Ergonomics Laboratory of the School of Industrial Engineering between 24 March and 1 April 1992. The purpose of this study was to determine which of two possible stimulus presentation media (CRT vs. LED) should be used for the subsequent bimanual experiments. The decision criterion for choosing which medium would be used was to pick the one providing a better fit to the Hick and Fitts performance models based on RT and MT regression coefficients of determination ($R^2$).

### 3.2 Methodology

Pilot Study I involved a unimanual aiming task with 54 different combinations of two stimulus presentation media, three levels of target alternatives, three target distances, and three target widths. Visual stimuli were presented to the subjects under two media conditions, cathode ray tube (CRT) and light emitting diode (LED). The task required the subject to hold an electrical conducting stylus in the dominant hand on a home position and to wait for the occurrence of a stimulus. For the CRT condition, the display was placed directly in front of the subjects at a distance of approximately 40 inches. For the LED condition, lights were mounted directly on the target board (Figure 3.1).

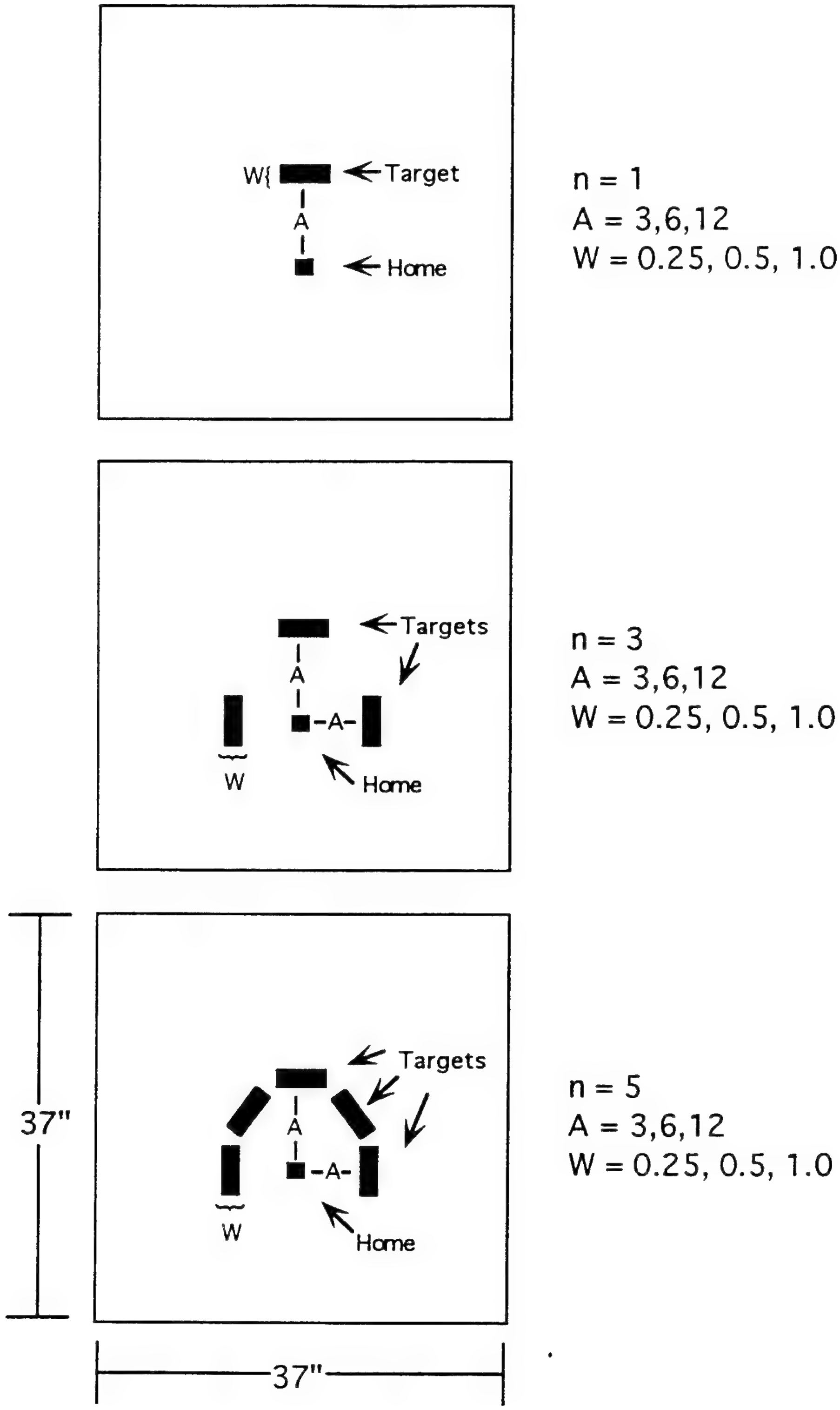


Figure 3.1. Pilot Study I Target Board (not drawn to scale).

Following stimulus detection, the subject lifted the stylus from the home position and touched the appropriate target with the stylus tip. If the target was successfully hit, the stimulus was removed. The subject returned the stylus to the home position and waited for the next stimulus. This process continued until all stimuli for that particular condition were presented. No pre-cuing of the stimulus was provided in either the CRT task or LED task.

Counterbalancing of the two media conditions was achieved by randomly assigning half of the subjects to the CRT task first, and the other half to the LED task first. Each of the 27 experimental conditions (Table 3.1) consisted of a block of 30 trials. Therefore, each subject performed 1620 separate trials. When more than one target was used, the target sequence was randomized with the restriction that each target was used an equal number of times. Thus, for three targets, each target was used ten times, and for five targets each target was used six times.

Subject waiting time from placing the stylus on the home position until stimulus arrival ranged from 0.82 to 2.40 seconds with a mean wait time of 1.62 seconds and a standard deviation of 0.51 seconds. Between blocks of trials, subjects waited while the experimenter manually changed the targets on the target board. Each experimental condition change took approximately two minutes. After 14 experimental conditions were completed, each subject was given a 10-minute rest break. The CRT and LED data were collected on separate days.

### 3.2.1 Independent Variables

Four independent variables were used in Pilot Study I. The stimulus display

medium was tested at two levels (CRT vs. LED). To address Hick's Law, the number of target alternatives (N = 1, 3, or 5) was varied. To address Fitts' Law, three movement amplitudes (3, 6 or 12 inches) and three target widths (0.25, 0.5, and 1.0 inches) were combined to produce six index of difficulty levels as illustrated in Table 3.1. The 2 x 3 x 3 x 3 factorial design resulted in 54 different experimental conditions.

Table 3.1. Pilot Study I IDs.

| | **A = 3"** | **A = 6"** | **A = 12"** |
|---|---|---|---|
| **W = 0.25"**<br>**N = 1, 3, 5** | 4.58 | 5.58 | 6.58 |
| **W = 0.5"**<br>**N = 1, 3, 5** | 3.58 | 4.58 | 5.58 |
| **W = 1.0"**<br>**N = 1, 3, 5** | 2.58 | 3.58 | 4.58 |

A = target amplitude, W = target width. IDs shown in bits. Nine ID conditions at three target alternative conditions resulted in 27 total conditions.

### 3.2.2 Dependent Variables

The three dependent variables in Pilot Study I were reaction time (RT), movement time (MT), and errors, defined as the subject hitting the wrong target. RT was defined as the measured time between the onset of the stimulus event and the initiation of movement. MT was defined as the measured time between initial movement and movement termination.

### 3.2.3 Control Variables

All subjects were verbally briefed on the purpose of the experiment and application areas where the results would be relevant. Written instructions were provided to each subject as an adjunct to the verbal instructions. All subjects performed the testing in the same laboratory space. Ambient temperature and lighting were controlled to the extent that all settings remained constant. All blocks, under all conditions were videotaped to observe eye movement.

### 3.2.4 Subjects

Six male subjects between 24 and 40 years of age (mean = 31.2) were tested. These subjects represented a fortuitous sample from the University of Oklahoma community. All were students in advanced or graduate programs and all were right-hand dominant. All subjects were non-paid volunteers and none had any experience with experimental aiming tasks.

### 3.2.5 Training

Each subject completed 20 conditions for training presented in blocks of 30 trials for both the CRT and LED conditions. Three subjects trained under the CRT condition first, three under the LED condition first. Subjects trained at all five ID levels (2.58, 3.58, 4.58, 5.58 and 6.58), and all three target alternative levels (N = 1, 3, and 5). An additional five conditions were chosen, one at each ID, with N and movement amplitude determined at random.

### 3.2.6 Experimental Apparatus

Pilot Study I used the following equipment:

1. Zenith 386-SX PC with color video display and task software
2. target response board (Figure 3.1)
3. metal stylus (11.27 grams)
4. straight-back chair
5. two videotape cameras.

The target response board used for the pilot study was 37 inches square and was covered with a soft black plastic mat (approx. 0.0625" thick) in which were cut 30 rectangular holes that served as targets (Figure 3.1). Under the plastic cover were pie-shaped galvanized steel wedges. The rectangular cut-outs were located 3, 6, and 12 inches from a central home position that was also cut from the plastic. The target cut-outs were located at 0, 45, 90, 135, 180, 225, 270, and 315 degrees, where 0 degrees is defined by the line running through the centrally located home position and parallel to the subject's frontal plane. This configuration resulted in targets located in quadrants I through IV of a Cartesian system with the home position at the origin.

Pilot Study I used only those targets in quadrants I and II at 0, 45, 90, 135, and 180 degrees. Targets were numbered from 1 to 5, beginning with the target to the subject's left at the 180 degree position.

Inside each of the cut-outs could be placed plastic inserts in which smaller rectangular openings were cut to produce target widths of 0.25, 0.5, and 1.0 inches. The home position was a 0.5-inch square cut out of the plastic.

For the CRT stimulus presentation condition, stimuli were presented on a CRT

positioned 40 inches directly in front of the subject and centered 18 inches above the target board. CRT height with respect to subject eye level was not adjusted, and thus varied with subject anthropometry and posture. For the LED stimulus presentation condition, five red, light emitting diodes (LED) were placed 4 inches from the home position between the 3 and 6 inch target rows and in-line with the respective targets. The stylus, fashioned from a steel scribe and tapered at one end, was wrapped in a plastic cover and wired to the computer's digital I/O port.

Eye movements were videotaped to get an idea of how frequently and in what pattern the eyes moved when viewing the CRT and LED stimuli. The tapes were not quantitatively analyzed.

### 3.2.7 Software

Separate software programs controlled the CRT and LED experiments due to the differing requirements of the stimuli. Except for the method of stimulus presentation, the programs were essentially the same. No pre-cuing of stimuli was used. Each program used the timing subroutine of Graves and Bradley (1987, 1988) to obtain millisecond accuracy.

The functions of the various modules of the controlling program for Pilot Study I are briefly discussed below and are listed in Table 3.2. Modules controlling the LED stimuli are identical except that the LED program contains no module to define target locations on the CRT, since the method used to present the stimulus was different.

**Module 1** defined array dimensions, initialized values, and defined functions used

by the millisecond timing routine. **Module 2** defined the target locations on the CRT. **Module 3** read the subject number from the keyboard, determined whether the current block ("run") was the first block tested for the particular subject, and ended the program if all conditions were tested. **Module 4** initialized the variables necessary to run the millisecond timer and read experimental conditions from keyboard input. **Module 5** began execution of a block of trials. For $N > 1$, Module 5 branched to either Module 8 or Module 9 where the stimulus presentation sequence was determined. Blank targets and home positions were drawn on the CRT screen and a test determined whether the stylus was on the home position. If so, the home position was illuminated. A random delay was then generated before the stimulus was presented by filling one of the targets on the screen. **Module 6** was the response timing routine. It determined the stimulus presentation time, the time when the stylus was removed from the home position and the time a target was hit. Time differences were then calculated to determine RT and MT. Errors were also determined. Dependent measures were stored in arrays. **Module 7** calculated means and standard deviations from the data stored in the arrays for a particular block of trials. **Module 8** displayed the block mean RT, mean MT, and number of errors for the experimenter. **Module 9** wrote the collected data to external files, recording the performance data and summary statistics. **Module 10,** called by Module 5 at the beginning of each set of 30 trials, randomized the target sequence for all $N = 3$ conditions. **Module 11** performed the same function as Module 10 for all $N = 5$ conditions.

Table 3.2. Pilot Study I CRT Controlling Program Modules.

| Name | Function |
|---|---|
| Module 1 | Initialize Program |
| Module 2[1] | Define Target Positions on CRT |
| Module 3 | Start/Stop Test |
| Module 4 | Input Experimental Conditions |
| Module 5 | Generate and Present Stimulus |
| Module 6 | Determine RT, MT, and Errors |
| Module 7 | Calculate Statistics |
| Module 8 | Display Block Results |
| Module 9 | Record Data |
| Module 10 | **N** = 3 Sequence Randomizer |
| Module 11 | **N** = 5 Sequence Randomizer |

### 3.3 Results and Analyses

Pilot Study I mean reaction times and movement times for the CRT and LED presentation media are tabulated in Table 3.3. Figure 3.2 presents RT regressed on $H_s$ and MT regressed on ID for the CRT and LED conditions.

#### 3.3.1 Reaction Time

Mean reaction time (RT) averaged across all conditions was 250 milliseconds with a standard deviation of 47 milliseconds. The mean CRT RT was 249 msec, with a standard deviation of 28 msec while the mean LED RT was 251 msec, with a standard deviation of 36 msec.

[1]This module is not included in the LED version.

Table 3.3. Pilot Study I RT and MT Means by Condition.

| | | CRT | | LED | |
|---|---|---|---|---|---|
| N | ID | RT | MT | RT | MT |
| 1 | 2.58 | 213 | 246 | 195 | 170 |
| 1 | 3.58 | 208 | 311 | 204 | 251 |
| 1 | 4.58 | 224 | 354 | 211 | 319 |
| 1 | 5.58 | 217 | 447 | 213 | 442 |
| 1 | 6.58 | 218 | 508 | 221 | 513 |
| 3 | 2.58 | 271 | 263 | 245 | 223 |
| 3 | 3.58 | 253 | 328 | 273 | 313 |
| 3 | 4.58 | 263 | 444 | 270 | 385 |
| 3 | 5.58 | 260 | 494 | 271 | 480 |
| 3 | 6.58 | 26 | 566 | 284 | 563 |
| 5 | 2.58 | 269 | 265 | 255 | 215 |
| 5 | 3.58 | 264 | 335 | 266 | 286 |
| 5 | 4.58 | 273 | 419 | 274 | 373 |
| 5 | 5.58 | 275 | 507 | 284 | 484 |
| 5 | 6.58 | 266 | 681 | 289 | 550 |
| Averaged Across N | | | | | |
| | 2.58 | 251 | 258 | 232 | 203 |
| | 3.58 | 242 | 325 | 248 | 283 |
| | 4.58 | 253 | 406 | 248 | 283 |
| | 5.58 | 250 | 483 | 256 | 462 |
| | 6.58 | 250 | 483 | 265 | 542 |
| Averaged Across ID | | | | | |
| 1 | | 216 | 373 | 209 | 335 |
| 3 | | 262 | 419 | 269 | 393 |
| 5 | | 269 | 441 | 273 | 381 |
| OVERALL | | 249 | 411 | 250 | 370 |

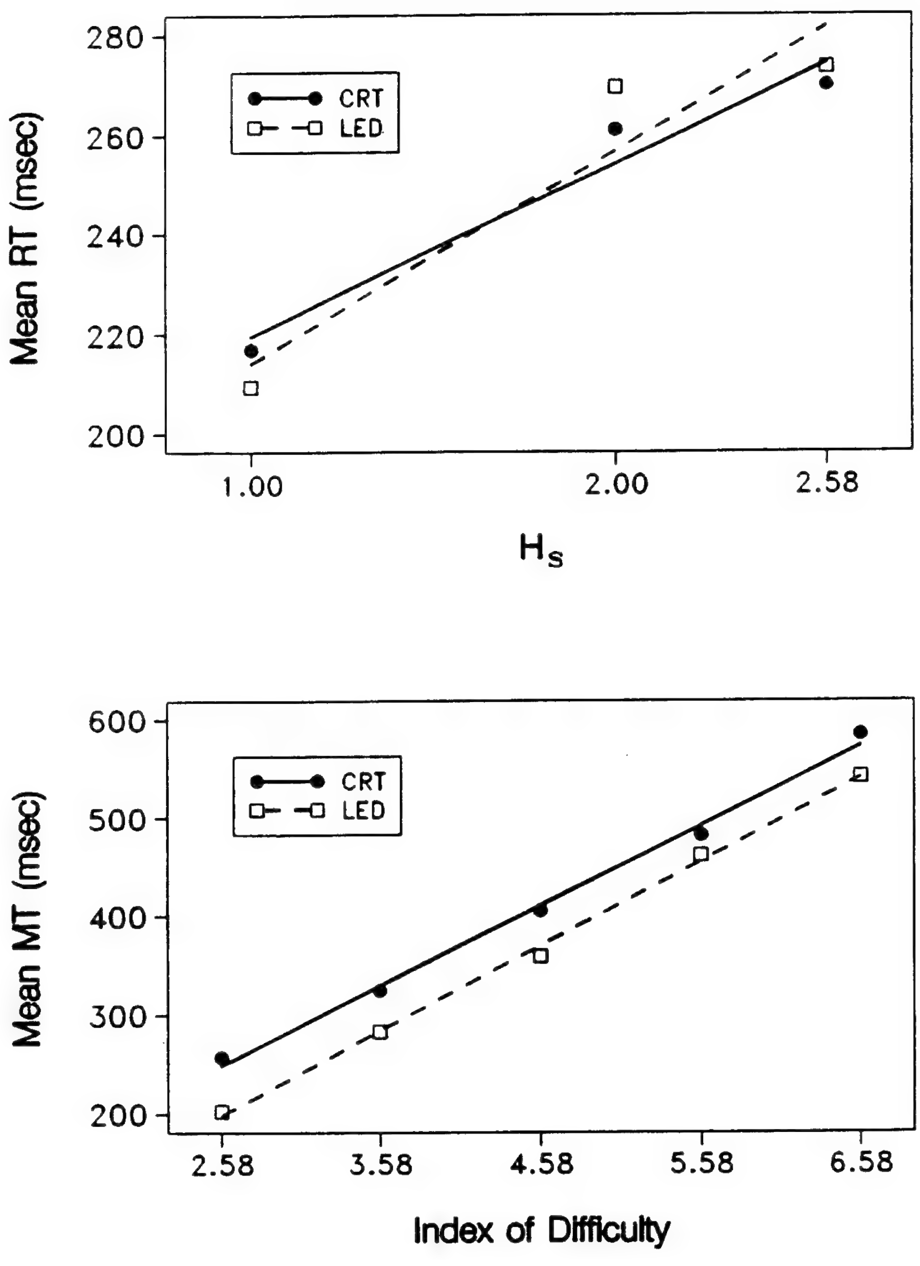


Figure 3.2. Pilot Study I RT and MT CRT-LED Comparison.

A 2 x 5 x 3 repeated measures analysis of variance (CONDITION x ID x N) was performed on the RT data treating subjects as a random factor. Table 3.4 presents the ANOVA summary. There was no significant RT difference between the CRT and LED presentation media (COND in Table 3.4). The number of target alternatives (N) was significant, $F(2,10) = 26.59$, $p = 0.0001$, with RT increasing as N increased. Index of difficulty (ID) was also significant, $F(4,20) = 9.09$, $p = 0.0002$, with RT increasing with increasing ID. The statistically significant N x COND interaction, $F(4,20) = 6.60$, $p = 0.0015$, is illustrated in Figure 3.2.

The top plot of Figure 3.2 presents RT regressed on $H_s$ for the CRT and LED conditions. The coefficients of determination ($R^2$) for these Hick's Law regressions were 0.954 for the CRT data and 0.904 for the LED data. Both RT regression line slopes were significantly different from zero ($p \leq 0.05$). There was no significant difference between the CRT and LED regression line slopes ($p = 0.305$, df = 5) nor between the predicted CRT and LED means ($p = 0.87$, df = 5).

Figure 3.3 presents the RT data regressed on $H_s$ for the CRT and LED conditions by ID. For the LED condition, notice that an upward shift in mean RT occurred with increasing ID. Variation also occurred under the CRT condition, but with no monotonic relationship to ID.

Table 3.4. RT and MT ANOVA.

PILOT STUDY I - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME

INDEPENDENT VARIABLES

CONDITION: CRT, LED
INDEX OF DIFF: 2.58, 3.58, 4.58, 5.58, 6.58
TARGETS: 1, 3, 5

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 63 | 5 | 15334 | 0.02 | 0.8920 |
| ID | 4 | 6216 | 20 | 3418 | 9.09 | 0.0002 |
| TARGETS | 2 | 126090 | 10 | 23712 | 26.59 | 0.0001 |
| COND*ID | 4 | 5725 | 20 | 4337 | 6.60 | 0.0015 |
| COND*TARGETS | 2 | 1527 | 10 | 6646 | 1.15 | 0.3556 |
| ID*TARGETS | 8 | 653 | 40 | 10263 | 0.32 | 0.9544 |
| COND*ID*TARGETS | 8 | 1314 | 40 | 7570 | 0.87 | 0.5513 |

PILOT STUDY I - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME

INDEPENDENT VARIABLES

CONDITION: CRT, LED
INDEX OF DIFF: 2.58, 3.58, 4.58, 5.58, 6.58
TARGETS: 1, 3, 5

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 77232 | 5 | 27153 | 14.22 | 0.0130 |
| ID | 4 | 2514779 | 20 | 80792 | 155.63 | 0.0001 |
| TARGETS | 2 | 119722 | 10 | 10380 | 57.67 | 0.0001 |
| COND*ID | 4 | 5813 | 20 | 18126 | 1.60 | 0.2123 |
| COND*TARGETS | 2 | 8513 | 10 | 10537 | 4.04 | 0.0518 |
| ID*TARGETS | 8 | 31040 | 40 | 58651 | 2.65 | 0.0198 |
| COND*ID*TARGETS | 8 | 32428 | 40 | 56417 | 2.87 | 0.0126 |

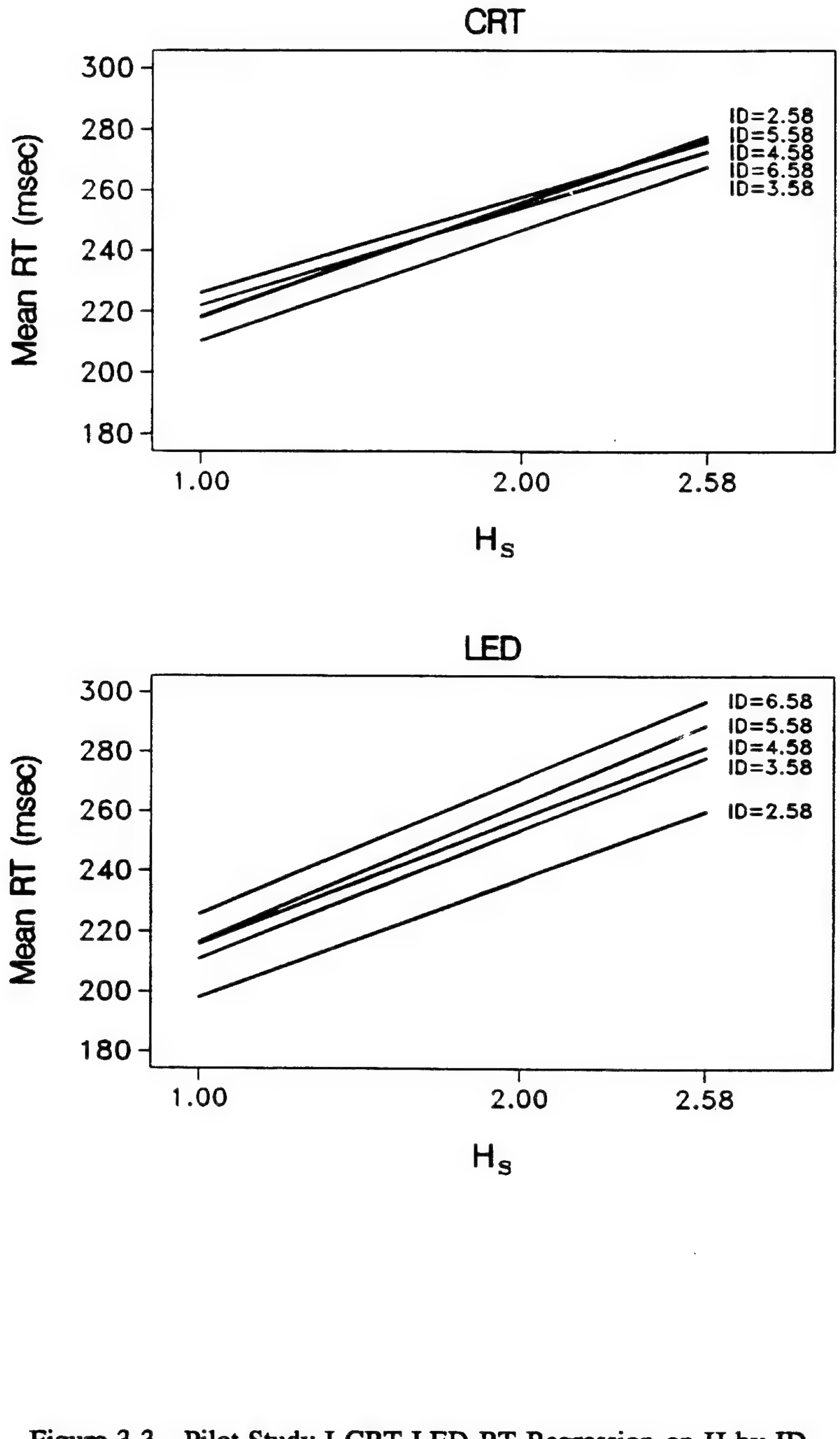


Figure 3.3. Pilot Study I CRT-LED RT Regression on H by ID.

### 3.3.2 Movement Time

Mean movement time (MT) averaged across all conditions was 391 milliseconds with a standard deviation of 123 milliseconds. The mean CRT MT was 411 msec, with a standard deviation of 128 msec while the mean LED MT was 370 msec, with a standard deviation of 135 msec. Average CRT and LED movement times under all combinations of conditions tested were presented in Table 3.3.

A 2 x 5 x 3 repeated measures analysis of variance (CONDITION x ID x N) with subjects treated as a random factor was conducted on the MT data (Table 3.4). There was a significant MT difference between the CRT and LED stimulus presentation media, $F(1,5) = 14.22, p = 0.013$. ID was significant, $F(4,20) = 155.63, p = 0.0001$, with higher MTs associated with higher IDs. The number of target alternatives was significant, $F(2,10) = 57.67, p = 0.0001$ with movement time increasing with increasing N. There were no statistically significant interactions.

The lower plot of Figure 3.2 presents MT regressed on ID for the CRT and LED conditions. The coefficients of determination ($\mathbf{R}^2$) for these Fitts' Law regressions were 0.99 for both the CRT data and the LED data. Tests of the hypothesis that the MT regression lines slopes did not differ from zero were rejected for both the CRT and LED conditions ($p \leq 0.0001$, df = 5). There was no significant difference between the CRT and LED regression line slopes ($p = 0.2663$, df = 5). However, as determined by the ANOVA, mean LED MT (370 msec) was significantly shorter ($p = 0.013$, df = 5) than mean CRT MT (411 msec).

Figure 3.4 presents the regressions of MT on ID for the CRT and LED data by

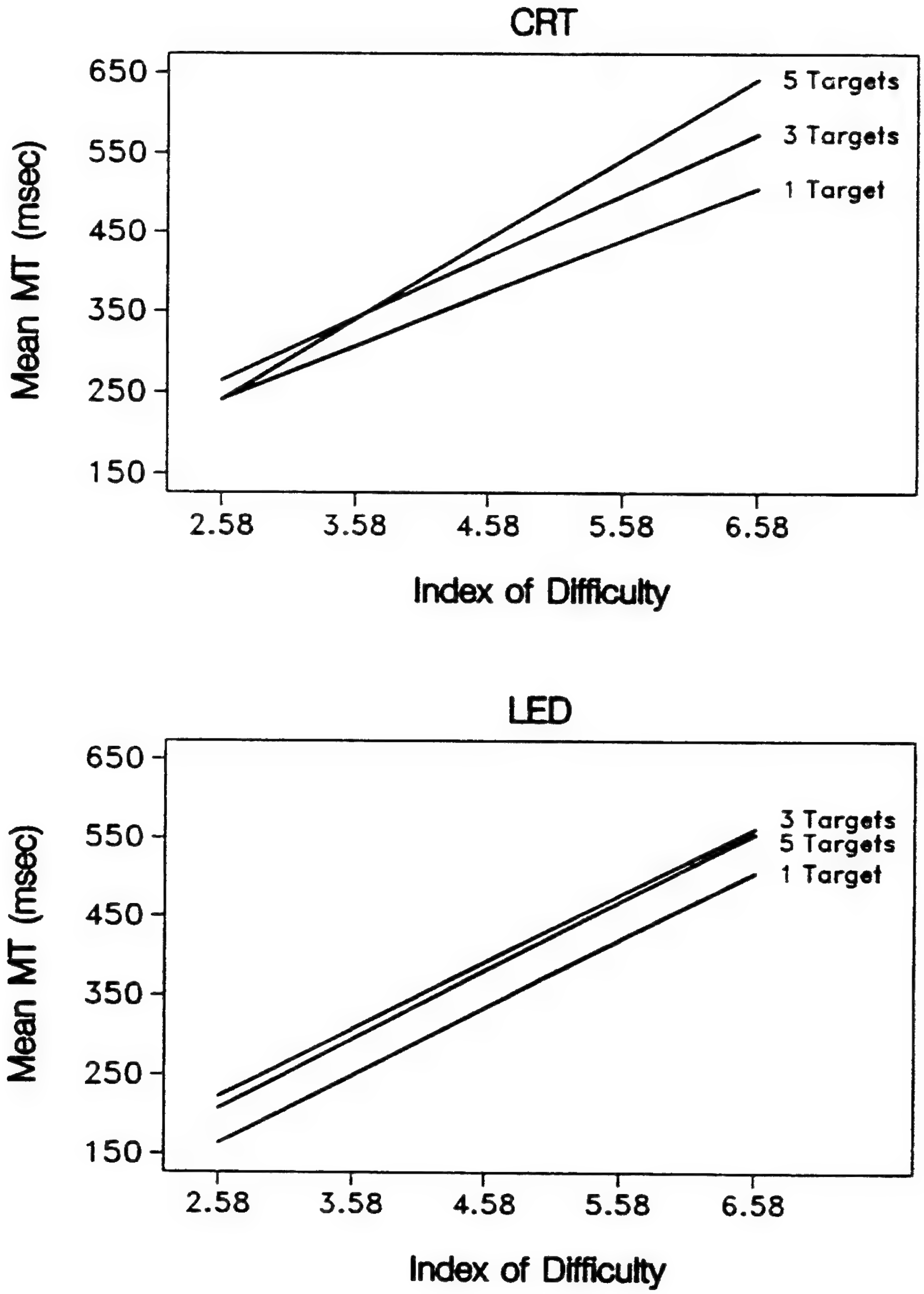


Figure 3.4. Pilot Study I CRT-LED MT Regressed on ID.

the number of target alternatives. Under the CRT condition, predicted MTs at ID = 2.58 were clustered around 250 msec. Increasing slopes with increases in N resulted in substantially different MTs at ID = 6.58. Under the LED condition, a distinct upward shift occurred from the N = 1 to the N = 3 and N = 5 conditions.

The RT coefficient of determination for the CRT stimulus presentation medium was slightly higher than the $R^2$ for the LED condition. However, neither the slopes nor the means of the regression lines were significantly different. Standard deviations were comparable. Coefficients of determination for the MT data were essentially identical for the two presentation media. Subjects were queried by the experimenter as to which stimulus medium was preferred after they had completed the entire sequence of CRT and LED trials. Without exception, all subjects said they preferred the LED medium.

### 3.4 Summary

In summary, Pilot Study I revealed the following:

1. RT was modeled equally well by Hick's Law for CRT and LED based on $R^2$
2. no significant CRT - LED RT difference occurred
3. MT was modeled equally well by Fitts' Law for CRT and LED based on $R^2$
4. MT was significantly faster for the LED condition
5. subjects unanimously preferred LED stimuli.

Based on the faster MT data and the positive subject comments, an LED stimulus array mounted directly on the target board was selected as the stimulus presentation medium for the bimanual experiments.

# CHAPTER IV

# PILOT STUDY II

## 4.1 Purpose

Pilot Study II was conducted at the University of Oklahoma in the Information Ergonomics Laboratory between 15 and 24 May 1992. The purpose of Pilot Study II was to test the functionality of a newly designed and constructed stimulus-response target board and the associated task software. Data were collected to evaluate Hick's Law and Fitts' Law under the bimanual paradigm, to compare the unimanual and bimanual tasks, and as a preliminary examination of the extent of MT synchrony between the hands.

## 4.2 Methodology

Under the paradigm of Pilot Study II, unimanual and bimanual aiming task data were collected for 110 conditions involving three target alternative levels, three movement amplitudes and three target widths. Bimanual tasks were performed under either equal-ID or unequal-ID conditions. Equal-ID conditions existed when the left hand and the right hand were moving to targets of equal index of difficulty. Unequal-ID conditions existed when the hands were moving to targets of differing indices of difficulty. Stimulus lights were illuminated randomly on the stimulus-response board. The subject responded as quickly and accurately as possible by lifting the stylus (styli) from the home position(s) and striking the appropriate target(s). The subject returned

the stylus (styli) to the home position(s) and waited for the next stimulus presentation. This process continued until all stimuli for that particular condition were presented. No pre-cuing of the stimulus event was provided.

The sequence of unimanual and bimanual conditions presented to the subjects was randomized. For each condition, a block of 20 trials was tested. Therefore, each subject performed 2200 separate trial movements (counting a bimanual movement as one movement).

Waiting time from the subject's placing the stylus on the home position until the time of the next stimulus presentation ranged from 0.82 to 2.50 seconds with a mean of 1.62 seconds and a standard deviation of 0.507 seconds. Between conditions, subjects waited while the experimenter manually changed the targets on the target board. Each experimental condition change took approximately one minute. After completing half of the experimental conditions, subjects were given a 20-minute rest break. Data for each subject were collected over two sessions.

### 4.2.1 Independent Variables

Five independent variables were manipulated for Pilot Study II. The first independent variable compared the unimanual vs. the bimanual conditions. Second, to evaluate Hick's Law, the number of targets (N) was set to one of three levels ($N = 1$, 2, or 4 targets per hand). Third, to evaluate Fitts' Law, index of difficulty (ID) was varied by manipulating movement amplitude (4, 8 and 16 inches) and target width (0.5, 1.0 and 2.0 inches). Table 4.1 presents the unimanual ID combinations used. The fourth independent variable was HAND (left or right). As the fifth variable, the task

difficulty of the opposite hand was also varied. Table 4.2 presents the bimanual ID combinations tested showing the left hand ID (IDL) and right hand ID (IDR).

Table 4.1. Pilot Study II Indices of Difficulty (ID).

| Amplitude (inches) | Width (inches) | ID (bits) |
|---|---|---|
| 4 | 2.0 | 2 |
| 4 | 1.0 | 3 |
| 4 | 0.5 | 4 |
| 8 | 2.0 | 3 |
| 8 | 1.0 | 4 |
| 16 | 1.0 | 5 |
| 16 | 0.5 | 6 |

Table 4.2. Pilot Study II Bimanual ID Combinations.

| | **IDR = 3** | **IDR = 4** | **IDR = 5** | **IDR = 6** |
|---|---|---|---|---|
| **IDL = 3** | 3.0/3.0 | 3.0/4.0 | 3.0/5.0 | 3.0/6.0 |
| **IDL = 4** | 4.0/3.0 | 4.0/4.0 | 4.0/5.0 | 4.0/6.0 |
| **IDL = 5** | 5.0/3.0 | 5.0/4.0 | 5.0/5.0 | 5.0/6.0 |
| **IDL = 6** | 6.0/3.0 | 6.0/4.0 | 6.0/5.0 | 6.0/6.0 |

Note: IDL = left hand index of difficulty
IDR = right hand index of difficulty
#/# = IDL/IDR

When more than one target was used, the target sequence was randomized with the restriction that each target was used an equal number of times. Thus, for two targets, each target was used ten times, and for four targets, each target was used five times.

Subsequent to data collection, a programming problem was discovered that resulted in a lack of balance in the number of bimanual unequal-ID conditions. Therefore, only data from the ***unimanual*** and *bimanual equal-ID* conditions were analyzed (Section 4.3).

Under the unimanual and bimanual N = 1 conditions, two movement directions (1 and 4) were each tested separately. See Section 4.2.6 for a discussion of physical target location and movement direction. Under the unimanual and bimanual N = 2 conditions, movement directions 1 and 4 were always tested together. Movement directions 2 and 3 were only tested under the N = 4 condition and not under the N = 1 or N = 2 conditions.

### 4.2.2 Dependent Variables

The three dependent variables for Pilot Study II were reaction time (RT), movement time (MT), and errors. Errors, defined as the subject striking the wrong target for N > 1, were automatically recorded by the software.

### 4.2.3 Control Variables

All subjects were verbally briefed on the purpose of the experiment and application areas where the results would be relevant. Written instructions (Appendix A) were used as an adjunct to the verbal instructions. Testing for all subjects was conducted in the same laboratory where ambient temperature control settings remained constant. Each subject wore a cotton pull-over shirt through which the electrical wires

leading from the styli were routed to minimize interference with subject movement. This was accomplished by threading the wires from behind the subject, through the neck and sleeves of the shirt, and down each arm. The wires then came out at the wrist and attached to each stylus. To accommodate videotaping (Section 4.2.8), standard room lighting was augmented with two 150-watt halogen lamps positioned to the sides and behind each subject.

### 4.2.4 Subjects

Nine male subjects were recruited from the University of Oklahoma student and staff population. All were right-hand dominant except one. All subjects were graduate students except one who was a U.S. Air Force NCO assigned to the 675th U.S. Air Force ROTC Detachment at the University of Oklahoma. The subjects ranged in age from 22 to 47 years (mean = 32.8 years). All subjects were non-paid volunteers. Approval for testing human subjects was obtained from the University of Oklahoma Institutional Review Board - Norman Campus (Appendix B). Appendix C provides a copy of the informed consent form presented to each subject.

### 4.2.5 Training

Subjects were trained at a movement amplitude of 12 inches and at target widths of 0.5, 1.0 and 2.0 inches. These levels resulted in training indices of difficulty of 3.58, 4.58 and 5.58 bits. All three target alternative conditions were used (N = 1, 2, and 4). Subjects performed blocks of 20 trials per condition and completed 20 conditions (all

nine bimanual and six unimanual tasks and five additional conditions selected arbitrarily by the experimenter). Subjects were trained on the unimanual task first.

### 4.2.6 Experimental Apparatus

The following equipment was used for Pilot Study II:

1. Zenith 386-SX PC with associated task software
2. LED Driver Interface Unit (DIU)
3. stimulus-response board with aluminum target disks (Figure 4.1)
4. two aluminum styli (mean mass = 8.517 grams)
5. long sleeve pull-over shirt
6. straight-back chair
7. two video cameras and a VCR
8. cotton gloves.

The bimanual stimulus-response board (SRB) was constructed in the Information Ergonomics Laboratory of the School of Industrial Engineering.[2] The SRB was a wooden, rectangular box attached to a wooden table. LED stimuli and aluminum target disks were mounted on the SRB (Figure 4.1). The stimulus-response surface of the SRB measured 24 inches wide by 42 inches long. It was constructed from a sheet of plexiglas and painted flat black to minimize glare from reflected light. Six inches laterally from either side of the short-axis center-line and six inches from the front edge were located

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[2]Dan Major, Technical Specialist, University of Oklahoma, School of Industrial Engineering is credited with building the LED DIU and assisting in the construction of the SRB based on experimental requirements.

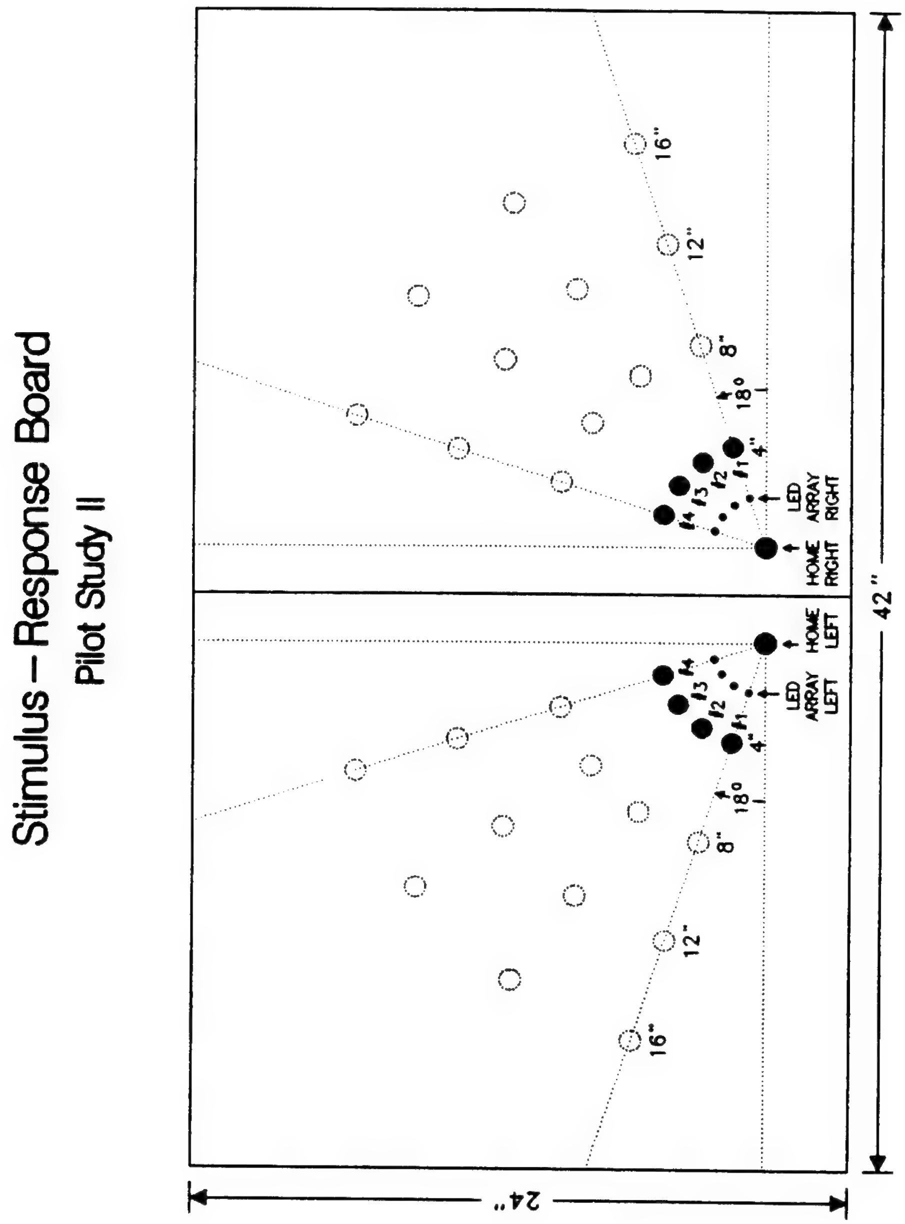


Figure 4.1. Bimanual Stimulus-Response Board.

two aluminum disks which served as the left and right home positions. They measured 0.5 inches in diameter and were 0.3125 inches high.

Radial lines 18 degrees apart starting from a line drawn through the home positions and perpendicular to the sagittal plane were used to locate holes drilled in the SRB surface. These holes were located on arcs 4, 8, 12, and 16 inches from the left and right home positions respectively. This resulted in 16 holes on each half of the board into which aluminum target disks could be placed. The targets were 0.5, 1.0 and 2.0 inches in diameter.

Movement directions were numbered one through four on the left and right sides beginning with the lateral direction. This resulted in the left #1 targets and the right #1 targets being mirror images. The design allowed for the placement of up to 16 targets per side.

Left and right styli were modified #10, aluminum knitting needles. Each was shortened to six inches and painted black. Wire leads were soldered to screws at the non-tapered end. The styli mass averaged 8.517 grams. Six styli were used during the experiment -- four were kept ready as back-ups.

On each side, mounted between the home positions and the first row of targets at the four-inch position were four high output (2000 mCd), red, light emitting diodes. Each LED in the array corresponded to one and only one movement direction. The LEDs were particularly bright to avoid any stimulus on/off ambiguity. When new, these LEDs had a clear plastic covering and a narrow viewing angle. That is, the LEDs were only bright when viewed directly from above. Brightness viewed from the side was significantly less. Therefore, it was necessary to roughen the surface of each LED to

provide a uniform, frosted finish. This effort resulted in a significant dispersion of light and a much wider field of stimulus presentation.

An LED Driver Interface Unit (DIU) was constructed to connect the LEDS and the styli to the computer's input/output (I/O) port. The driver circuitry consisted of a 2N3904 transistor in an emitter-follower configuration that powered the individual LEDs through a current-limiting resistor.

### 4.2.7 Software

The software used to control Pilot Study II was similar in principle to that used for Pilot Study I. However, significant modifications were required to accommodate the bimanual movement. As with Pilot Study I, no pre-cue was used. Millisecond timing accuracy was achieved through the use of assembly language subroutines by Graves and Bradley (1987, 1988). The modules of the controlling program for Pilot Study II are listed in Table 4.3 and are defined below.

**Module 1** defined array dimensions, initialized variables, and defined a function used by the millisecond timing routine. **Module 2** read input from the keyboard for subject number and asked the operator whether the current run was the initial run or a continuation of earlier testing. Module 2 also tested for completion of the experiment and ended the program if all conditions had been tested. **Module 3** initialized the variables necessary to run the millisecond timer and incremented the experimental condition. **Module 4** read an external file containing the 110 conditions and randomized the presentation sequence of those conditions. This sequence of conditions was written

to an external file for each subject. **Module 5** output experimental conditions to the CRT for experimenter confirmation. **Module 6** began execution of the block of 20 trials for the current condition. **Module 7** determined whether the current condition was unimanual or bimanual. If bimanual, then the number of targets for that condition was determined. The specific target locations were then identified and Module 7 branched to the appropriate sequence randomizer (Modules 16 - 19). **Module 8** presented the appropriate bimanual stimuli and collected subject response data. Reaction time left and reaction time right (RTL, RTR) and movement time left and movement time right (MTL, MTR) were determined as well as errors committed. **Module 9** tested for the right-hand unimanual condition and proceeded similar to Module 7. **Module 10** presented the appropriate right-hand stimuli and collected the response data. RTR, MTR and errors were determined. **Module 11** tested for the left-hand unimanual condition and proceeded similar to Module 7. **Module 12** presented the appropriate left-hand stimuli and collected the response data (RTL, MTL and errors). **Module 13** calculated statistics for the 20 trials in each block (means and standard deviations for RTL, RTR, MTL and MTR and the number of errors left and right). **Module 14** displayed these summary statistics on the CRT. **Module 15** stored the performance data in a sequential data file for each subject. **Module 16** randomized the target presentation sequence for the left hand, N = 4 condition. **Module 17** randomized the target presentation sequence for the right hand, N = 4 condition. **Module 18** randomized the target presentation sequence for the left hand, N = 2 condition. **Module 19** randomized the target presentation sequence for the right hand, N = 2 condition.

Table 4.3. Pilot Study II Program Modules.

| Name | Function |
|---|---|
| Module 1 | Initialize Program |
| Module 2 | Start/Stop Experiment |
| Module 3 | Set Timer |
| Module 4 | Input Experimental Conditions |
| Module 5 | Output Experimental Conditions |
| Module 6 | Begin Test |
| Module 7 | Test for Bimanual Condition |
| Module 8 | Present Stimuli - Collect Data |
| Module 9 | Test for Right Hand Condition |
| Module 10 | Present Stimulus - Collect Data |
| Module 11 | Test for Left Hand Condition |
| Module 12 | Present Stimulus - Collect Data |
| Module 13 | Calculate Statistics |
| Module 14 | Display Condition Results |
| Module 15 | Store Data |
| Module 16 | Left **N** = 4 Sequencer |
| Module 17 | Right **N** = 4 Sequencer |
| Module 18 | Left **N** = 2 Sequencer |
| Module 19 | Right **N** = 2 Sequencer |

### 4.2.8 Videotaping

All Pilot Study II trials were videotaped for possible biomechanical analysis. Room lighting was augmented by two 150-watt halogen lamps to illuminate the tip of each stylus which was marked with reflective tape. The lamps were placed to either side and behind the subjects. This taping required that the subject wear a dark shirt with long sleeves and dark gloves to minimize the light reflected from the body and to maximize the light reflected from the tape.

## 4.3 Results and Analyses

Pilot Study II was conducted as an initial test of the bimanual stimulus-response target board. Nine subjects were tested in May 1992. The videotaping was not analyzed due to time limitations. Following a discussion of location differences, analyses will be presented in the following sequence:

- RT - unimanual vs. bimanual performance
- MT - unimanual vs. bimanual performance
- MT hand synchrony.

### 4.3.1 Target Location Differences

The effect of different movement directions was analyzed for the N = 4, unimanual condition because of the deterministic assignment of targets. The bimanual conditions were not analyzed for location effects because they would be confounded with the spatial asymmetry that may have existed during any trial. That is, on any bimanual trial, directions #4 left and #1 right may have represented the intended targets. It would,

therefore, be difficult to determine whether the direction was affecting performance or the spatial asymmetry, or both.

A 2 x 4 x 4 repeated measures analysis of variance (HAND x ID x LOC) on MT for the N = 4, unimanual condition identified significant effects due to movement direction ($F = 3.03$, $p = 0.0491$), ID ($F(3,24) = 84.75$, $p \leq 0.0001$) and HAND ($F(1,8) = 6.99$, $p = 0.0295$). A significant HAND x LOC interaction existed ($F(3,24) = 3.73$, $p = 0.0249$). A post-hoc Tukey test showed no significant difference in movement direction ($\alpha = 0.05$, df = 24) confirming that the significance was marginal.

### 4.3.2 RT - Unimanual vs. Bimanual Equal-ID

Figure 4.2 presents mean RT data plotted as a function of ID for each of the three target alternative sets. Appendix D presents the mean RT data for all conditions. A 2 x 2 x 4 x 3 repeated measures analysis of variance (COND x N x ID x HAND) was conducted on the combined unimanual and bimanual equal-ID RT data (Table 4.4). Unimanual vs. bimanual COND was significant, $F(1,8) = 62.81$, $p \leq 0.0001$ with the unimanual reactions faster (239 vs. 339 msec). The number of target alternatives (N) was significant, $F(2,16) = 38.61$, $p \leq 0.0001$, with RT increasing with increasing N. ID was significant, $F(3,24) = 21.31$, $p \leq 0.0001$, with RT increasing with increasing ID. HAND was significant, $F(1,8) = 7.92$, $p = 0.0227$, with the left hand faster than the right (284 vs. 294 msec). No interactions with HAND were significant except the three-way N x ID x HAND interaction. All other interactions were significant.

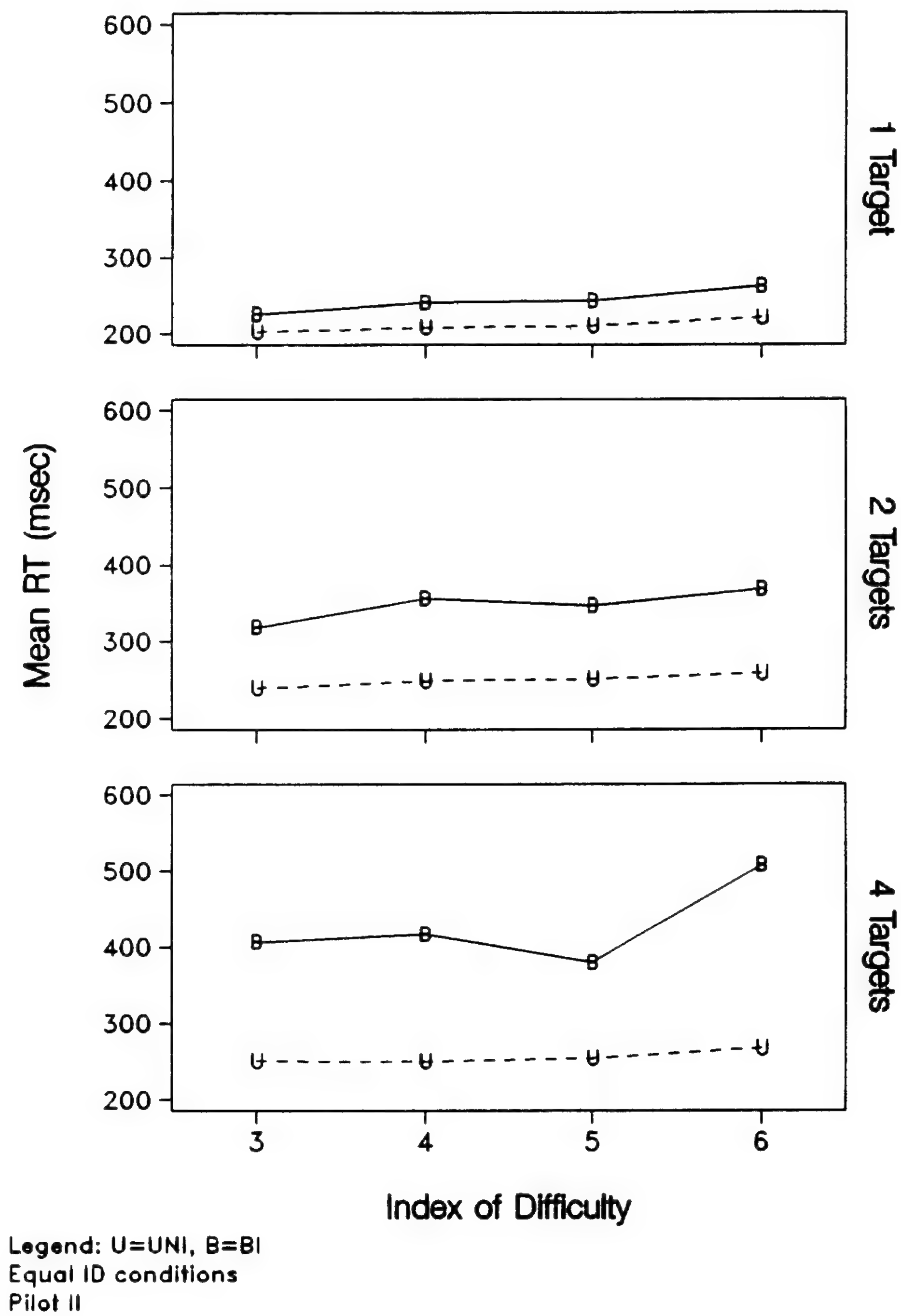


Figure 4.2. Unimanual-Bimanual Comparison of RT vs. ID by N.

Table 4.4. Pilot Study II RT ANOVA.

PILOT STUDY II - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, EQUAL IDCONDITIONS

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 1086309 | 8 | 138368 | 62.81 | 0.0001 |
| HAND | 1 | 9861 | 8 | 9960 | 7.92 | 0.0227 |
| ID | 3 | 100807 | 24 | 37852 | 21.31 | 0.0001 |
| TARGETS | 2 | 966562 | 16 | 200266 | 38.61 | 0.0001 |
| COND*HAND | 1 | 269 | 8 | 1227 | 1.76 | 0.2218 |
| COND*ID | 3 | 36335 | 24 | 35066 | 8.29 | 0.0006 |
| HAND*ID | 3 | 712 | 24 | 2935 | 1.94 | 0.1501 |
| COND*TARGETS | 2 | 349214 | 16 | 97728 | 28.59 | 0.0001 |
| HAND*TARGETS | 2 | 2039 | 16 | 5562 | 2.93 | 0.0822 |
| ID*TARGETS | 6 | 41984 | 48 | 49023 | 6.85 | 0.0001 |
| COND*HAND*ID | 3 | 26 | 24 | 2453 | 0.08 | 0.9679 |
| COND*HAND*TARGETS | 2 | 275 | 16 | 2207 | 1.00 | 0.3909 |
| COND*ID*TARGETS | 6 | 33928 | 48 | 60818 | 4.46 | 0.0012 |
| HAND*ID*TARGETS | 6 | 2715 | 48 | 6459 | 3.36 | 0.0076 |
| COND*HAND*ID*TARGETS | 6 | 1228 | 48 | 7975 | 1.23 | 0.3068 |

Separate repeated measures ANOVAs (Table 4.5) were conducted on the RT data for each of the levels of N (Appendix E). COND, ID and the COND x ID interaction were all significant at all target alternative levels. HAND was significant at N = 2 and N = 4.

Except at N = 1, the unimanual vs. bimanual condition differences are clearly evident from Figure 4.2. Notice that for the unimanual condition, RT increased as ID increased, though the increase is small. However, the N x COND interaction is evident. As N increased, the difference between the unimanual and bimanual conditions increased.

### 4.3.3 MT - Unimanual vs. Bimanual Equal-ID

Appendix D presents the mean MT values for all combinations of conditions tested. Figure 4.3 presents the MT data as a function of ID for each level of N. A very large unimanual vs. bimanual difference was observed. A 2 x 2 x 3 x 4 repeated measures analysis of variance (COND x N x ID x HAND) was conducted on the combined unimanual and bimanual MT data (Table 4.6). COND (unimanual vs. bimanual) was significant, $F(1,8) = 50.52$, $p \leq 0.0001$, with the unimanual reactions faster (335 vs. 574 msec). The number of target alternatives was significant, $F(2,16) = 43.59$, $p \leq 0.0001$, with MT increasing with increasing N. ID was significant, $F(3,24) = 203.55$, $p \leq 0.0001$, with higher IDs resulting in longer movements (277 vs. 381 vs. 475 vs. 684 msec). HAND was significant, $F(1,8) = 5.56$, $p = 0.0461$, with the right hand faster than left (435 vs. 473 msec). Significant interactions occurred for COND x ID, $F(3,24) = 51.08$, $p \leq 0.0001$, and COND x N, $F(2,16) = 35.37$, $p \leq 0.0001$.

Table 4.5. Pilot Study II RT ANOVA by Target Alternative Levels.

PILOT STUDY II - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, EQUAL IDCONDITIONS BY TAR

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6

TARGETS=1

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 37491 | 8 | 3435 | 87.31 | 0.0001 |
| HAND | 1 | 995 | 8 | 1901 | 4.19 | 0.0750 |
| ID | 3 | 13971 | 24 | 4098 | 27.27 | 0.0001 |
| COND*HAND | 1 | 0 | 8 | 584 | 0.01 | 0.9435 |
| COND*ID | 3 | 1494 | 24 | 3022 | 3.95 | 0.0201 |
| HAND*ID | 3 | 323 | 24 | 1492 | 1.73 | 0.1869 |
| COND*HAND*ID | 3 | 263 | 24 | 1213 | 1.74 | 0.1862 |

TARGETS=2

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 339792 | 8 | 38260 | 71.05 | 0.0001 |
| HAND | 1 | 2248 | 8 | 2927 | 6.14 | 0.0382 |
| ID | 3 | 21887 | 24 | 42504 | 4.12 | 0.0172 |
| COND*HAND | 1 | 499 | 8 | 1288 | 3.10 | 0.1165 |
| COND*ID | 3 | 5105 | 24 | 33365 | 1.22 | 0.3226 |
| HAND*ID | 3 | 2538 | 24 | 3858 | 5.26 | 0.0062 |
| COND*HAND*ID | 3 | 484 | 24 | 5863 | 0.66 | 0.5848 |

TARGETS=4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 1058241 | 8 | 194401 | 43.55 | 0.0002 |
| HAND | 1 | 8657 | 8 | 10694 | 6.48 | 0.0345 |
| ID | 3 | 106933 | 24 | 40273 | 21.24 | 0.0001 |
| COND*HAND | 1 | 45 | 8 | 1561 | 0.23 | 0.6440 |
| COND*ID | 3 | 63664 | 24 | 59496 | 8.56 | 0.0005 |
| HAND*ID | 3 | 565 | 24 | 4044 | 1.12 | 0.3614 |
| COND*HAND*ID | 3 | 507 | 24 | 3352 | 1.21 | 0.3275 |

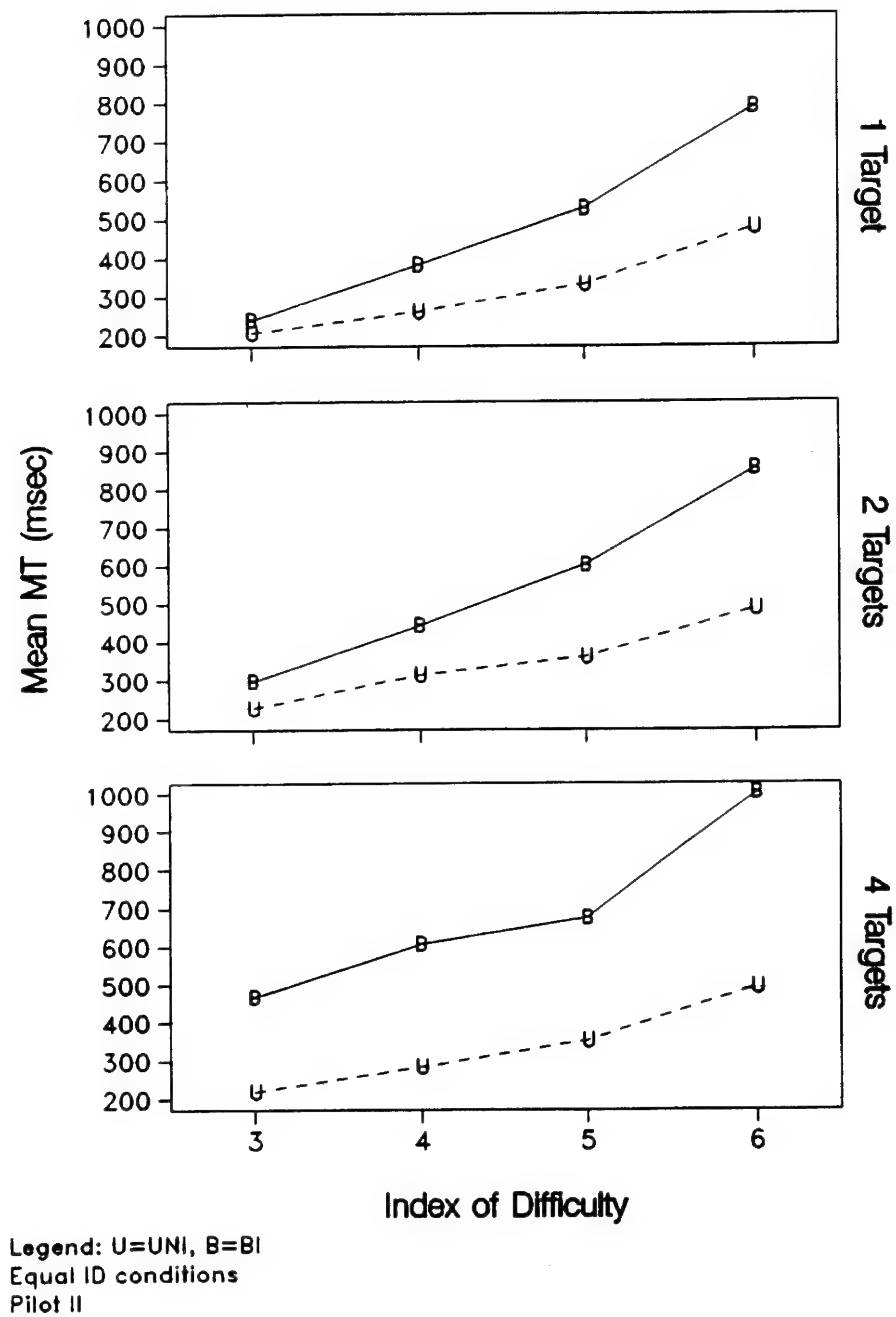


Figure 4.3. Unimanual-Bimanual Comparison of MT vs. ID by N.

Table 4.6. Pilot Study II MT ANOVA.

PILOT STUDY II - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, EQUAL IDCONDITIONS

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 6167993 | 8 | 976799 | 50.52 | 0.0001 |
| HAND | 1 | 160102 | 8 | 230261 | 5.56 | 0.0461 |
| ID | 3 | 9723514 | 24 | 382166 | 203.55 | 0.0001 |
| TARGETS | 2 | 894916 | 16 | 164230 | 43.59 | 0.0001 |
| COND*HAND | 1 | 2449 | 8 | 162227 | 0.12 | 0.7372 |
| COND*ID | 3 | 1136771 | 24 | 178032 | 51.08 | 0.0001 |
| HAND*ID | 3 | 60297 | 24 | 247406 | 1.95 | 0.1485 |
| COND*TARGETS | 2 | 687587 | 16 | 155526 | 35.37 | 0.0001 |
| HAND*TARGETS | 2 | 3645 | 16 | 64398 | 0.45 | 0.6438 |
| ID*TARGETS | 6 | 31549 | 48 | 196653 | 1.28 | 0.2827 |
| COND*HAND*ID | 3 | 24258 | 24 | 192035 | 1.01 | 0.4053 |
| COND*HAND*TARGETS | 2 | 7374 | 16 | 65953 | 0.89 | 0.4283 |
| COND*ID*TARGETS | 6 | 41533 | 48 | 191039 | 1.74 | 0.1322 |
| HAND*ID*TARGETS | 6 | 22074 | 48 | 281390 | 0.63 | 0.7073 |
| COND*HAND*ID*TARGETS | 6 | 19280 | 48 | 339735 | 0.45 | 0.8386 |

Separate repeated measures ANOVAs were conducted on the MT data for each of the levels of N (Table 4.7). COND, ID and the COND x ID interaction were all significant for all target alternative levels. As presented in Figure 4.3, the unimanual vs. bimanual difference increased with increasing ID (significant COND x ID interaction). This difference was amplified as the number of targets increased (significant COND x N interaction).

### 4.3.4 MT Synchrony

One measure of limb synchrony is the mean absolute difference in movement time between left and right hands. Figure 4.4 plots this difference by ID for all target alternative sets. Based on these plots, very little difference existed in the bimanual equal-ID condition at N = 1 and at ID = 3 and ID = 4. However, at ID = 5, the absolute difference was greater than 100 milliseconds and at ID = 6, the difference was greater than 150 milliseconds. One hand or the other was slower. This effect is more pronounced for the N = 2 and N = 4 conditions. From these plots it appears that bimanual movements under the conditions tested were not synchronous.

Table 4.7. Pilot Study II MT ANOVA by Target Alternative Levels.

PILOT STUDY II - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, EQUAL IDCONDITIONS BY TAR

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6

TARGETS=1

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 985966 | 8 | 191713 | 41.14 | 0.0002 |
| HAND | 1 | 35768 | 8 | 76372 | 3.75 | 0.0889 |
| ID | 3 | 3323967 | 24 | 227896 | 116.68 | 0.0001 |
| COND*HAND | 1 | 103 | 8 | 83123 | 0.01 | 0.9233 |
| COND*ID | 3 | 377540 | 24 | 138612 | 21.79 | 0.0001 |
| HAND*ID | 3 | 5059 | 24 | 134925 | 0.30 | 0.8251 |
| COND*HAND*ID | 3 | 5837 | 24 | 115263 | 0.41 | 0.7507 |

TARGETS=2

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 1462588 | 8 | 361367 | 32.38 | 0.0005 |
| HAND | 1 | 52651 | 8 | 111911 | 3.76 | 0.0883 |
| ID | 3 | 3236778 | 24 | 174255 | 148.60 | 0.0001 |
| COND*HAND | 1 | 432 | 8 | 62455 | 0.06 | 0.8199 |
| COND*ID | 3 | 466663 | 24 | 151919 | 24.57 | 0.0001 |
| HAND*ID | 3 | 25779 | 24 | 200171 | 1.03 | 0.3968 |
| COND*HAND*ID | 3 | 4820 | 24 | 227225 | 0.17 | 0.9158 |

TARGETS=4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 4407026 | 8 | 579245 | 60.87 | 0.0001 |
| HAND | 1 | 75327 | 8 | 106376 | 5.66 | 0.0445 |
| ID | 3 | 3194318 | 24 | 176667 | 144.65 | 0.0001 |
| COND*HAND | 1 | 9288 | 8 | 82601 | 0.90 | 0.3707 |
| COND*ID | 3 | 334102 | 24 | 78540 | 34.03 | 0.0001 |
| HAND*ID | 3 | 51533 | 24 | 193700 | 2.13 | 0.1231 |
| COND*HAND*ID | 3 | 32881 | 24 | 189281 | 1.39 | 0.2700 |

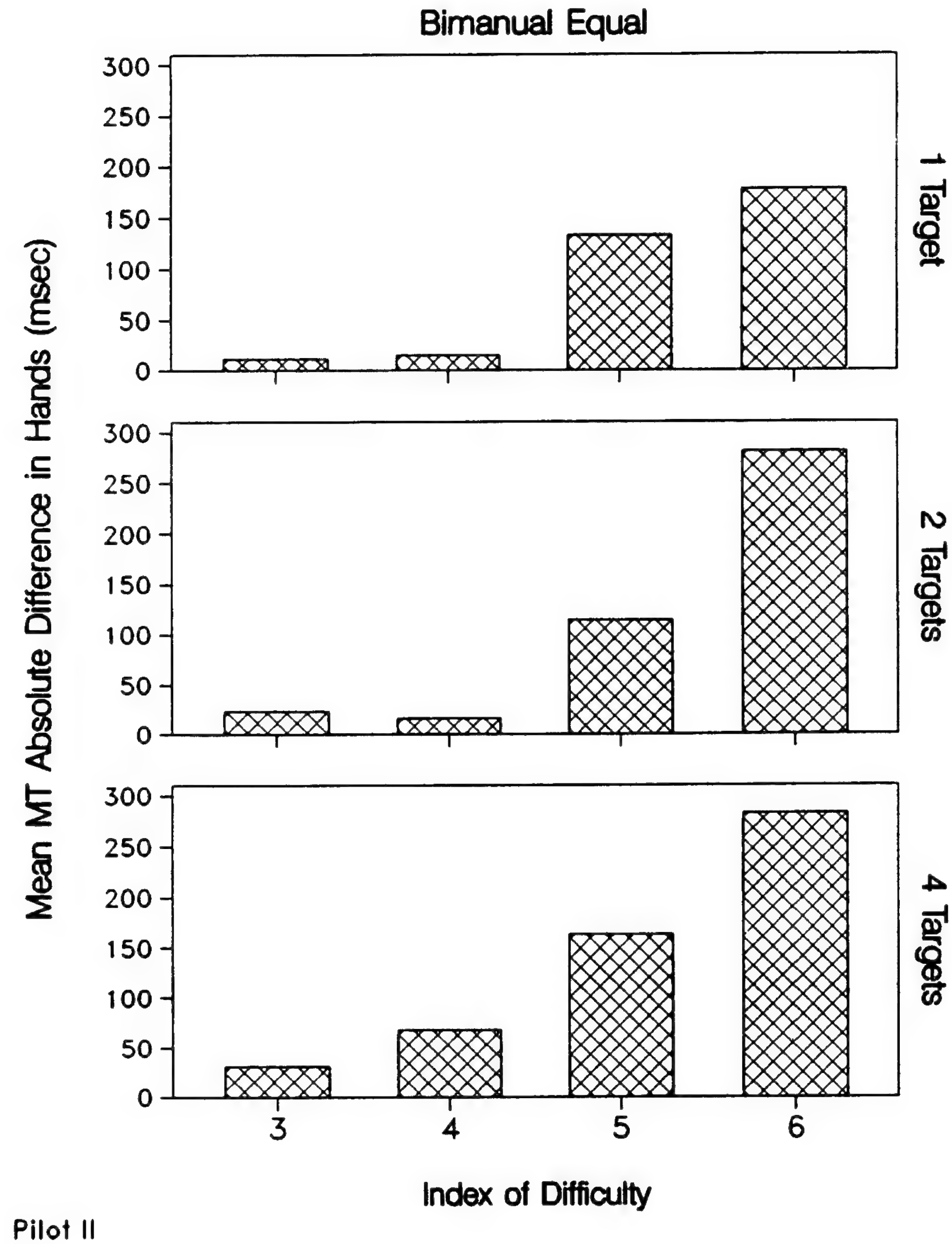


Figure 4.4. Pilot Study II Mean Hand MT Difference.

## 4.4 Summary

Conclusions based on the unimanual, N = 4 condition are summarized as follows:

- movement direction had a marginally significant effect on MT ($p$ = 0.0491)
- a significant HAND x LOC interaction occurred ($p$ = 0.0249).

Based on the unimanual and bimanual equal-ID RT data, the following may be concluded:

- unimanual RT was faster than bimanual RT
- RT increased with increasing N
- RT increased with increasing ID
- the left hand reacted faster than the right.

Based on the unimanual and bimanual equal-ID MT data, the following may be concluded:

- unimanual MT was faster than bimanual MT
- MT increased with increasing ID
- MT increased with increasing N
- the right hand moved faster than the left.

Pilot Study II provided several useful insights into the bimanual paradigm, the experimental apparatus and the experimental procedures. The following lessons were learned and formed the basis for improvements for the Main Study.

1. Videotaping interfered with subject movement. Each stylus had reflective tape placed on its tip to enable video recording for later biomechanical analysis. To clearly see the tape on the film, most subjects had to hold their hands in an awkward position (arms

adducted and flexed, wrists flexed). It is possible that this modified performance.

2. Subject stimulus anticipation was apparent. This statement is based on observation. Often it was noticed that subjects would leave the home position before a stimulus event occurred. The controlling program always waited for the subject to return before providing a stimulus. In some instances, this may have resulted in aberrant data.

3. Stimulus presentation at a location should be randomized and all target locations should be used under all conditions instead of just at locations 1 or 2 under the N = 1 condition, or only locations 1 and 2 under the N = 2 condition.

4. ID determination should be simplified. Since Fitts' Law is well established, one movement amplitude and one target width should define ID instead of using several amplitudes and widths which result in the same ID.

5. Too many conditions were tested. The Main Study needed to be simpler in terms of the number of conditions.

6. Misses need to be recorded as a way of reducing the skew of the data and also to record only valid data with full information transmitted.

# CHAPTER V

# MAIN STUDY

## 5.1 Purpose

The Main Study was conducted at the University of Oklahoma in the Information Ergonomics Laboratory between 6 August and 24 August 1992. The purposes of the Main Study were: (1) to evaluate Hick's Law and Fitts' Law under the bimanual paradigm with *unequal-IDs*, (2) to compare performance of the unimanual and bimanual tasks, (3) to evaluate performance synchrony when asymmetric task conditions existed between the hands, and (4) to determine the validity of combining Hick's Law and Fitts' Law for unimanual and bimanual total response time models.

## 5.2 Methodology

The Main Study was similar to Pilot Study II as described in Chapter IV with three significant differences. First, whereas target locations were selected deterministically in Pilot Study II, they were randomized for each condition tested in the Main Study. Second, 72 conditions were tested compared with 110 conditions in Pilot Study II. Third, no videotaping of subject performance was conducted.

As in Pilot Study II, LED stimulus lights were illuminated at random on the Stimulus-Response Board. The subject responded as quickly and accurately as possible by lifting the stylus (styli) from the home position(s) and striking the appropriate

target(s). The subject then returned the stylus (styli) to the home position(s) and waited for the next stimulus presentation. This process continued until all stimuli for that particular condition were presented. The 72 conditions were tested in blocks of 20 trials. Counting a bimanual movement as a single movement, this resulted in 1440 separate movements for each of the 20 subjects tested.

Catch trials were used to discourage and minimize premature responses. Pilot Study II indicated that some subjects may have perceived a "stimulus rhythm" and attempted to anticipate stimulus onset. The catch trial (described in Section 5.2.7) was employed to help interrupt any stimulus rhythm that may have existed. No pre-cuing of the stimulus event was provided.

All data for a given subject were collected on the same day in a period of approximately four hours. After 36 conditions were completed, the subject was given a 30-minute rest break.

### 5.2.1 Independent Variables

Five independent variables were manipulated for the Main Study. The first independent variable was the unimanual condition versus the bimanual condition. Second, to evaluate Hick's Law, the number of targets (N) was varied across three levels (N = 1, 2 or 4 targets per hand). Third, to evaluate Fitts' Law, index of difficulty (ID) was varied by manipulating movement amplitude (8 and 16 inches) and target width (0.5, 1.0 and 2.0 inches) to produce four indices of difficulty (3, 4, 5 and 6). Table 5.1 summarizes the combinations used. The fourth independent variable was the hand used (left or right). The fifth independent variable was the task difficulty of the opposite hand

(OPID). Table 5.2 classifies the resulting 72 combinations used. Table 5.3 presents a matrix of the bimanual ID combinations used in the Main Study.

Table 5.1. Indices of Difficulty (ID).

| Amplitude (inches) | Width (inches) | ID (bits) |
|---|---|---|
| 8 | 2.0 | 3 |
| 8 | 1.0 | 4 |
| 16 | 1.0 | 5 |
| 16 | 0.5 | 6 |

Table 5.2 Classification of Seventy-Two Testing Conditions.

| | Variables | # Cond |
|---|---|---|
| **Unimanual** | | |
| Left Hand | N = {1,2,4} x ID = {3,4,5,6} | 12 |
| Right Hand | N = {1,2,4} x ID = {3,4,5,6} | 12 |
| **Bimanual** | | |
| Equal-ID | N = {1,2,4} x (IDL{3,4,5,6} = IDR{3,4,5,6}) | 12 |
| Unequal-ID | N = {1,2,4} x (IDL{3,4,5,6} ≠ IDR{3,4,5,6}) | 36 |

Table 5.3. Bimanual ID Combinations.

| | **IDR = 3** | **IDR = 4** | **IDR = 5** | **IDR = 6** |
|---|---|---|---|---|
| **IDL = 3** | 3.0/3.0 | 3.0/4.0 | 3.0/5.0 | 3.0/6.0 |
| **IDL = 4** | 4.0/3.0 | 4.0/4.0 | 4.0/5.0 | 4.0/6.0 |
| **IDL = 5** | 5.0/3.0 | 5.0/4.0 | 5.0/5.0 | 5.0/6.0 |
| **IDL = 6** | 6.0/3.0 | 6.0/4.0 | 6.0/5.0 | 6.0/6.0 |

Note: IDL = left hand index of difficulty
IDR = right hand index of difficulty
#/# = IDL/IDR

### 5.2.2 Dependent Variables

The four dependent variables for the Main Study were reaction time (RT), movement time (MT), errors and misses. Errors, defined as the subject striking the wrong target for $N > 1$, were automatically recorded by the software. Misses, defined as the subject not making contact with the intended target on the first attempt, were manually counted and logged by the experimenter.

### 5.2.3 Control Variables

All subjects were verbally briefed on the purpose of the experiment and application areas where the results would be relevant. Written instructions (Appendix A) were used as an adjunct to the verbal instructions. Testing for all subjects was conducted in the same laboratory where ambient temperature control settings remained constant. Each subject wore a cotton pull-over shirt through which the electrical wires leading from the styli were routed to minimize interference with subject movement. This

was accomplished by threading the wires from behind the subject, through the neck and sleeves of the shirt, and down each arm. The wires then came out at the wrist and attached to each stylus.

### 5.2.4 Subjects

Twenty subjects were recruited from the University of Oklahoma student and staff population. All subjects were non-paid volunteers and right-hand dominant. Sixteen of the twenty were male; fifteen were graduate students. Ages ranged from 20 to 47 years (mean = 30.4 years). Four of the 20 had served as subjects in Pilot Study II two months earlier with no additional task performance between studies. Approval for testing human subjects was obtained from the University of Oklahoma Institutional Review Board-Norman Campus (Appendix B). Appendix C is a copy of the informed consent form presented to each subject.

### 5.2.5 Training

Subject training for the Main Study was conducted at movement amplitudes of 8 and 16 inches and target widths of 2.0, 1.0 and 0.5 inches (ID = 3, 4, 5 and 6). These were the same conditions that subjects performed during data collection. All four unimanual left and unimanual right conditions were performed once in blocks of 20 trials, and all sixteen bimanual ID conditions were performed once (Table 5.3) in blocks of 20 trials. Unimanual condition training was completed first. The number of target alternatives cycled repeatedly through N = 1, N = 2, and N = 4. Each subject was thus trained on 24 conditions, and performed 480 aiming movements in response to

visual stimuli.

### 5.2.6 Experimental Apparatus

The Main Study used the following equipment (see Section 4.2.6 for details):

1. Zenith 386-SX PC with associated task software
2. LED Driver Interface Unit (DIU)
3. stimulus-response board (SRB) with targets (Figure 4.1)
4. two aluminum styli (mean mass = 8.517 grams)
5. long sleeve pull-over shirt
6. straight-back chair.

### 5.2.7 Software

The software[3] used for the Main Study was similar in principle to that used for Pilot Study II. Significant modifications were made to provide randomization of the target locations. As in the pilot studies, no pre-cue was used. However, the following catch trial procedure was employed. With a 0.1 probability, the routine that determined the wait time between the styli returning to the home positions and the next stimulus presentation produced an additional delay averaging 0.49 seconds. Without the catch trial, stimulus events occurred between 1.31 and 2.50 seconds after contact of the styli with the home positions.

Millisecond accuracy was obtained in the timing modules for the RT and MT

[3]The BASIC programs that controlled these experiments can be obtained from Dr. Robert E. Schlegel, School of Industrial Engineering, University of Oklahoma.

performance measures through the use of assembly language subroutines from Graves and Bradley (1987, 1988) and Smith and Puckett (1984). The software modules used in the Main Study are listed in Table 5.4 and are defined below.

**Module 1** defined array dimensions, initialized values, and defined a function used by the millisecond timing routine. **Module 2** read input from the keyboard for subject number, and asked the operator whether the current run was the initial run or a continuation of earlier testing. Module 2 also tested for completion of the experiment and ended the program if all conditions had been tested. **Module 3** initialized the variables necessary to run the millisecond timer and incremented the experimental condition. **Module 4** read an external file containing the 72 conditions with target locations randomized by another BASIC program for the particular subject. Module 4 then randomized the presentation sequence of the 72 conditions. This sequence was then written to an external file for each subject as a historical record. **Module 5** output experimental conditions to a CRT for experimenter confirmation. **Module 6** began execution of the block of 20 trials for the current condition. **Module 7** determined whether the current condition was unimanual or bimanual. If bimanual, then the number of targets for that condition was determined. The specific target locations were then determined. Module 7 then branched to the appropriate sequence randomizer (Modules 16 - 29). **Module 8** presented the appropriate bimanual stimuli and collected subject response data. Reaction time left and reaction time right (RTL, RTR) and movement time left and movement time right (MTL, MTR) were determined as well as errors committed. **Module 9** tested for the right-hand unimanual condition and proceeded

similar to Module 7. **Module 10** presented the appropriate right-hand stimuli and collected response data. RTR, MTR and errors were determined. **Module 11** tested for the left-hand unimanual condition and proceeded similar to Module 7. **Module 12** presented the appropriate left-hand stimuli and collected response data. RTL, MTL and errors were determined. **Module 13** calculated statistics for the 20 trials (means and standard deviations for RTL, RTR, MTL, MTR and the number of errors left and right). **Module 14** displayed these statistics on the CRT. **Module 15** stored performance data in a sequential data file for each subject. **Modules 16** through **29** randomized the target presentation sequences. Each module handled a particular case for HAND (left or right), IDL (3, 4, 5 or 6), IDR (3, 4, 5 or 6) and N (2 or 4).

Table 5.4. Main Study Program Modules.

| | |
|---|---|
| Module 1 | Initialize Program |
| Module 2 | Start/Stop Experiment |
| Module 3 | Set Timer |
| Module 4 | Input Experimental Conditions |
| Module 5 | Output Experimental Conditions |
| Module 6 | Begin Test |
| Module 7 | Test for Bimanual Condition |
| Module 8 | Present Stimuli - Collect Data |
| Module 9 | Test for Right Hand Condition |
| Module 10 | Present Stimulus - Collect Data |
| Module 11 | Test for Left Hand Condition |
| Module 12 | Present Stimulus - Collect Data |
| Module 13 | Calculate Statistics |
| Module 14 | Display Condition Results |
| Module 15 | Store Data |
| Module 16 | Left N = 4 Sequence Randomizer |
| Module 17 | Right N = 4 Sequence Randomizer |
| Module 18 | Right N = 2 Sequence Randomizer (5&6) |
| Module 19 | Right N = 2 Sequence Randomizer (5&7) |
| Module 20 | Right N = 2 Sequence Randomizer (5&8) |
| Module 21 | Right N = 2 Sequence Randomizer (6&7) |
| Module 22 | Right N = 2 Sequence Randomizer (6&8) |
| Module 23 | Right N = 2 Sequence Randomizer (7&8) |
| Module 24 | Left N = 2 Sequence Randomizer (1&2) |
| Module 25 | Left N = 2 Sequence Randomizer (1&3) |
| Module 26 | Left N = 2 Sequence Randomizer (1&4) |
| Module 27 | Left N = 2 Sequence Randomizer (2&3) |
| Module 28 | Left N = 2 Sequence Randomizer (2&4) |
| Module 29 | Left N = 2 Sequence Randomizer (3&4) |

## 5.3 Results and Analysis

Over a three-week period, 28,800 observations were recorded for 20 subjects. Performance data were recorded in separate files for each subject. Each observation corresponding to a single experimental trial contained 21 variables (Table 5.5). The data were then analyzed using the Statistical Analysis System (SAS) on a VAX 8650 mainframe computer. All ANOVA tests were performed using repeated measures tests and the SAS **PROC GLM** (repeated) option with subjects treated as a random factor.

When plotted, MT data from one of the 20 subjects showed a strong divergence from the other 19 subjects as the index of difficulty of the opposite hand increased. For this reason, this subject's data were removed from all analyses.

Two observations for one subject were recorded erroneously for unexplained reasons. In the first instance, a unimanual right task recorded a hit on target #10 (which did not exist) with a reaction time of 14 milliseconds and a movement time of seven milliseconds. An equally unexplained recording for a bimanual task recorded a hit to target #10 with an RTL of 27 milliseconds, an MTL of 328 milliseconds, an RTR of 16 milliseconds and an MTR of 13 milliseconds. Clearly these observations were recorded in error and were deleted from all analyses.

As a measure of terminal accuracy, misses, previously defined as an aiming movement that resulted in the subject missing the target on the first attempt, were recorded manually by the experimenter. This was achieved by close scrutiny of each subject's performance for each trial. If the subject missed the target, the hand and trial number for that miss were annotated. Close misses were distinguished from hits by observing the LEDs which did not extinguish unless a successful hit was made. This

method did not differentiate errors from misses. If a miss was also an error, it was counted as a miss. Errors were recorded separately by the controlling software.

Table 5.5. Data Record Labels.

| Variable | Name |
|---|---|
| 1. SUBJECT NUMBER | SUBNUM |
| 2. EXPERIMENT NUMBER | EXP |
| 3. CONDITION NUMBER | COND |
| 4. TRIAL NUMBER | TRIAL |
| 5. HAND CONDITION | HAND |
| 6. NUMBER OF TARGETS LEFT | NL |
| 7. NUMBER OF TARGETS RIGHT | NR |
| 8. MOVEMENT AMPLITUDE LEFT | AL |
| 9. MOVEMENT AMPLITUDE RIGHT | AR |
| 10. TARGET WIDTH LEFT | WL |
| 11. TARGET WIDTH RIGHT | WR |
| 12. STIMULUS LOCATION LEFT | LCL |
| 13. TARGET HIT LEFT | HITL |
| 14. ERROR LEFT | ERORL |
| 15. STIMULUS LOCATION RIGHT | LCR |
| 16. TARGET HIT RIGHT | HITR |
| 17. ERROR RIGHT | ERORR |
| 18. REACTION TIME LEFT | RTL |
| 19. MOVEMENT TIME LEFT | MTL |
| 20. REACTION TIME RIGHT | RTR |
| 21. MOVEMENT TIME RIGHT | MTR |

Anytime a miss occurred, it first had to be perceived by the subject as having occurred. A second reaction was then combined with a second movement to the target. This correction could have resulted in several hundred milliseconds added to MT. RT was not directly affected. Therefore, MT observations contained in the subject miss data were eliminated from the analysis. See Section 5.3.9 for more details on miss results.

Reaction times and movement times below 100 milliseconds were also eliminated (Wargo, 1967). Even though catch trials accounted for 10 per cent of all trials (on average) some subject anticipatory behavior undoubtedly occurred. Subject anticipation may account for some recorded RTs below 100 milliseconds. Without justification, Fowler et al. (1991) repeated any trial with an RT below 90 milliseconds or an MT below 30 milliseconds. Based on the results of the pilot studies, it was felt that any MT below 100 milliseconds should be eliminated.

As stated earlier, the controlling programs counted and recorded every time a subject hit a target that was not indicated by the target LED. This event outcome was considered an error. Very few errors occurred. In fact, only 0.49 per cent of the total left and right movements resulted in a terminal error.[4] This was much less than expected since the bimanual movement requirements are rather difficult and the experimenter believed that this difficulty would manifest itself by a larger error count. All observations that ended in terminal error were removed from all temporal analyses. No error analysis was conducted.

In summary, all observations with RTs or MTs below 100 milliseconds and all

[4]Only 222 errors occurred in the 45,600 total left and right unimanual and bimanual movements.

observations involving a miss or an error were eliminated prior to analysis. Under the bimanual conditions, only the MT data for the hand involved in the miss were removed. The RT data for that hand were retained, as were the contralateral hand MT data since those data were error/miss free. This overall scheme resulted in approximately 5 per cent of the data being eliminated prior to data summary and analysis.

Because of the skewness that results from this particular type of performance task (Henry, 1961), **median** RTs and MTs were used for analysis instead of means in order to diminish the effect of outlying data (Jagacinski and Monk, 1985). The median, as a measure of central tendency, is less sensitive to the effect of outliers than is the mean. The bias that may be introduced by using medians when comparing samples of unequal size should not affect the analysis significantly since 19 subjects were used and blocks of 20 trials per condition were tested (Miller, 1988, 1991). Only when data were eliminated under the constraints listed above would an unequal number of trials per condition occur. Therefore, for each of the 72 conditions, median reaction times and median movement times were determined. These medians (median of a block of 20 trials) were then used as the performance measure for each subject and task combination for summary plots, ANOVA, contrasts and correlation analysis.

Following a discussion of target location differences, data summaries and analyses will be presented in the following sequence:

1. unimanual and bimanual equal-ID RT
2. bimanual equal-ID vs. unequal-ID RT
3. unimanual and bimanual equal-ID MT
4. bimanual equal-ID vs. unequal-ID MT

5. RT-MT relationships

6. RT differences between hands

7. MT differences between hands

8. bimanual performance models.

Regression equations for each of the RT and MT combinations were calculated from the data and examined for fit. Analysis of variance was employed to determine significant main factors affecting the performance measures. Post-hoc contrasts were used for paired comparisons. The overall experimental error was held at $\alpha = 0.05$. Comparison-wise error is controlled by the Bonferroni method (Hays, 1988) and the Tukey's multiple comparison procedure (Montgomery, 1984).

### 5.3.1 Target Location Differences

Even though performance differences may occur as a function of movement direction, an initial assumption for this study was that subject performance (RT and MT) for all four target locations on each side would be equivalent for a given ID and N. This assumption was based on the belief that there was no practical way to design a target board that allowed for multiple target alternatives without creating spatial difference relationships and the resultant performance differences inherent in the movement asymmetry. That is to say, performance differences are naturally created by placing multiple targets on a board, since they can not all be placed in the same position. If locations were adjusted spatially for equivalent performance, then the IDs would no longer be the same because distance would change.

Figure 5.1 presents the movement time means and standard deviations collapsed across target size and subject for each left and right location at the 8 and 16 inch distances. Table 5.6 presents the left and right mean MT values by movement direction at N = 4 and averaged across ID and subject. Movement direction differences were tested for a main effect on movement time under the N = 4, unimanual condition. Movement directions are numbered from one to four beginning with the lateral direction. This results in the left #1 targets and the right #1 targets being mirror images.

Data were analyzed using a repeated measures ANOVA with subjects treated as a random factor. The following statistical model was used to test for movement direction effects:

$$Y_{ijk} = \mu + HAND_i + ID_j + HAND{\times}ID_{ij} + LOC_k +$$

$$HAND{\times}LOC_{ik} + ID{\times}LOC_{jk} + HAND{\times}ID{\times}LOC_{ijk} + \epsilon_{ijk},$$

where

$Y_{ijk}$ = MT for the $i^{th}$ hand, the $j^{th}$ index of difficulty, and the $k^{th}$ location

$\mu$ = mean

$HAND_i$ = hand (left,right)

$ID_j$ = index of difficulty (3,4,5,6)

$LOC_k$ = movement direction (1,2,3,4)

$\epsilon_{ijkl}$ = random error.

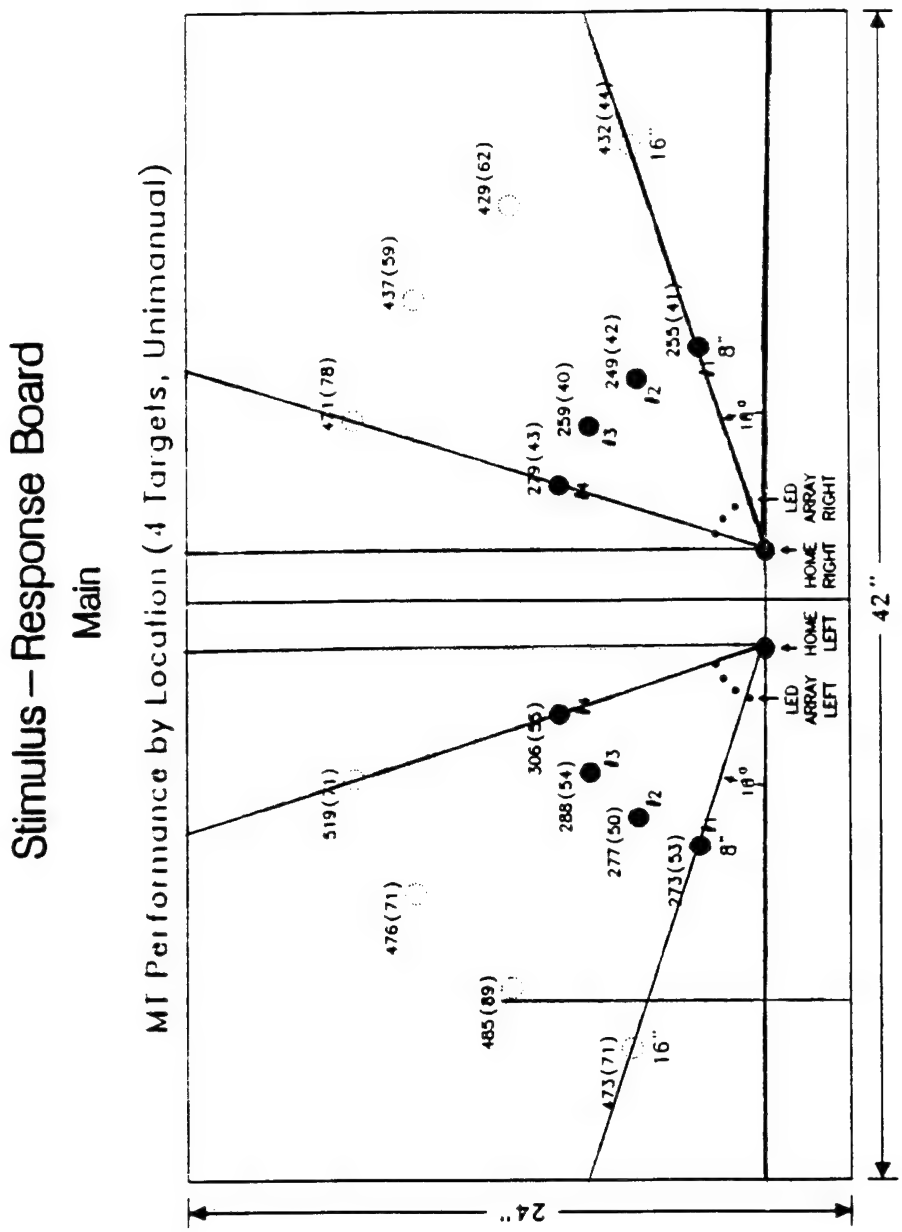


Figure 5.1. Stimulus-Response Board with MT Mean (Std.Dev.) by Location.

Table 5.6. MT Mean by Movement Direction and Hand (Unimanual, N = 4).

| | Hand | |
|---|---|---|
| **Direction** | **Left** | **Right** |
| **1** | 373 | 343 |
| **2** | 381 | 339 |
| **3** | 382 | 348 |
| **4** | 413 | 375 |

Table 5.7 presents the ANOVA results. Movement direction (LOC) was significant, $F(3,54) = 39.11$, $p \leq 0.0001$. Post-hoc Tukey contrasts showed that directions 1, 2 and 3 did not differ from each other but all were significantly different from direction 4 ($\alpha = 0.05$, df = 54).

Table 5.7. MT ANOVA for Movement Direction (Unimanual, N = 4).

| **Source** | **df** | **SSQ** | **Error df** | **F-value** | **P-value** |
|---|---|---|---|---|---|
| HAND | 1 | 196776 | 18 | 20.97 | 0.0002 |
| ID | 3 | 6740095 | 54 | 313.57 | 0.0002 |
| LOC | 3 | 125601 | 54 | 39.11 | 0.0001 |
| HAND*ID | 3 | 20610 | 54 | 2.08 | 0.1131 |
| HAND*LOC | 3 | 3170 | 54 | 0.93 | 0.4344 |
| ID*LOC | 9 | 19996 | 162 | 2.16 | 0.0272 |
| HAND*ID*LOC | 9 | 12590 | 162 | 1.31 | 0.2347 |

Because MT performance for direction 4 (left and right) was significantly slower than for directions 1 through 3, the percentage of hits for each direction was determined. If direction 4 were used substantially more than the other directions, then it would have had a damaging effect on the validity of the analytical results. Table 5.8 presents the percentage of times each movement direction was used at each left and right ID combination. Notice that stimulus events in each direction were evenly distributed.

### 5.3.2 RT - Unimanual and Bimanual Equal-ID

Table 5.9 presents the means and standard deviations for RT under all conditions as a function of $H_s$ (stimulus information). Table 5.10 presents the RT means and standard deviations under all conditions as a function of ID. Figure 5.2 presents unimanual and bimanual RT as a function of ID by N.

Unimanual RT data were analyzed using a 2 x 4 x 3 repeated measures ANOVA (N x ID x HAND) treating subjects as a random factor (Table 5.11). There were three significant main effects on RT. The number of target alternatives[5] was significant, $F(2,36) = 66.78$, $p = 0.0001$, with RT increasing as the number of target alternatives increased. ID was significant, $F(3,54) = 21.79$, $p \leq 0.0001$ with RT increasing as ID increased. HAND was statistically significant, $F(1,18) = 7.29$, $p = 0.0146$, with the left hand slightly faster than the right (244 vs. 250 msec). The HAND x N interaction was significant, $F(2,36)$, $p = 0.0138$.

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[5]Please note, the main effect of target alternative levels (N) is labeled "Targets" on the SAS output tables.

Table 5.8. Percentage of Use for Each Movement Direction.

FREQUENCY PERCENTS FOR EACH LOCATION

| INDEX LEFT HAND | INDEX RIGHT HAND | LOCATION 1 | 2 | 3 | 4 |
|---|---|---|---|---|---|
| NONE | 3 | 23 | 23 | 26 | 28 |
| NONE | 4 | 26 | 23 | 25 | 27 |
| NONE | 5 | 28 | 26 | 20 | 26 |
| NONE | 6 | 24 | 27 | 26 | 23 |
| 3 | NONE | 26 | 23 | 24 | 27 |
| 4 | NONE | 25 | 23 | 26 | 26 |
| 5 | NONE | 24 | 20 | 26 | 29 |
| 6 | NONE | 24 | 24 | 23 | 29 |
| 3 | 3 | 25 | 24 | 26 | 25 |
| 3 | 4 | 25 | 24 | 25 | 25 |
| 3 | 5 | 25 | 25 | 25 | 24 |
| 3 | 6 | 25 | 24 | 25 | 26 |
| 4 | 3 | 25 | 23 | 26 | 25 |
| 4 | 4 | 24 | 27 | 24 | 26 |
| 4 | 5 | 23 | 25 | 26 | 26 |
| 4 | 6 | 24 | 26 | 25 | 25 |
| 5 | 3 | 27 | 23 | 24 | 26 |
| 5 | 4 | 24 | 25 | 25 | 26 |
| 5 | 5 | 25 | 22 | 25 | 28 |
| 5 | 6 | 25 | 25 | 25 | 24 |
| 6 | 3 | 26 | 24 | 26 | 25 |
| 6 | 4 | 24 | 27 | 24 | 26 |
| 6 | 5 | 26 | 24 | 25 | 25 |
| 6 | 6 | 25 | 24 | 27 | 24 |
| | | == | == | == | == |
| | MEAN % | 24.9 | 24.5 | 25.1 | 25.5 |

Table 5.9. Mean RT by Stimulus Information.

| Hand | Index of Difficulty | Opposite Index of Difficulty | Mean and Std for Reaction Time (msec) $H_s = 1.00$ | $H_s = 1.58$ | $H_s = 2.32$ |
|---|---|---|---|---|---|
| Left | 3 | None | 218 ± 28 | 233 ± 27 | 250 ± 31 |
| Left | 3 | 3 | 236 ± 25 | 333 ± 85 | 389 ± 90 |
| Left | 3 | 4 | 244 ± 32 | 336 ± 85 | 376 ± 112 |
| Left | 3 | 5 | 251 ± 57 | 353 ± 94 | 424 ± 174 |
| Left | 3 | 6 | 267 ± 64 | 365 ± 93 | 424 ± 192 |
| Left | 4 | None | 220 ± 22 | 238 ± 25 | 253 ± 37 |
| Left | 4 | 3 | 245 ± 29 | 337 ± 97 | 393 ± 103 |
| Left | 4 | 4 | 258 ± 56 | 343 ± 117 | 392 ± 112 |
| Left | 4 | 5 | 256 ± 46 | 367 ± 129 | 426 ± 168 |
| Left | 4 | 6 | 265 ± 57 | 382 ± 149 | 391 ± 109 |
| Left | 5 | None | 235 ± 29 | 253 ± 37 | 268 ± 44 |
| Left | 5 | 3 | 251 ± 35 | 351 ± 79 | 425 ± 116 |
| Left | 5 | 4 | 264 ± 41 | 379 ± 117 | 461 ± 119 |
| Left | 5 | 5 | 275 ± 47 | 403 ± 110 | 509 ± 201 |
| Left | 5 | 6 | 281 ± 48 | 430 ± 204 | 495 ± 194 |
| Left | 6 | None | 241 ± 33 | 255 ± 39 | 268 ± 39 |
| Left | 6 | 3 | 267 ± 48 | 372 ± 111 | 436 ± 129 |
| Left | 6 | 4 | 275 ± 65 | 379 ± 107 | 428 ± 134 |
| Left | 6 | 5 | 269 ± 36 | 405 ± 129 | 513 ± 171 |
| Left | 6 | 6 | 272 ± 49 | 461 ± 163 | 524 ± 170 |
| Right | 3 | None | 217 ± 26 | 247 ± 31 | 257 ± 33 |
| Right | 3 | 3 | 238 ± 27 | 339 ± 82 | 378 ± 68 |
| Right | 3 | 4 | 248 ± 29 | 336 ± 89 | 385 ± 106 |
| Right | 3 | 5 | 249 ± 31 | 348 ± 67 | 428 ± 148 |
| Right | 3 | 6 | 270 ± 44 | 343 ± 78 | 441 ± 156 |
| Right | 4 | None | 220 ± 27 | 252 ± 42 | 265 ± 40 |
| Right | 4 | 3 | 244 ± 33 | 326 ± 65 | 371 ± 75 |
| Right | 4 | 4 | 259 ± 50 | 332 ± 74 | 400 ± 108 |
| Right | 4 | 5 | 255 ± 43 | 366 ± 105 | 400 ± 92 |
| Right | 4 | 6 | 259 ± 31 | 353 ± 79 | 429 ± 175 |
| Right | 5 | None | 232 ± 24 | 256 ± 33 | 276 ± 40 |
| Right | 5 | 3 | 250 ± 38 | 365 ± 93 | 438 ± 127 |
| Right | 5 | 4 | 268 ± 46 | 396 ± 129 | 452 ± 128 |
| Right | 5 | 5 | 273 ± 50 | 431 ± 125 | 530 ± 158 |
| Right | 5 | 6 | 274 ± 61 | 394 ± 103 | 505 ± 149 |
| Right | 6 | None | 237 ± 30 | 264 ± 44 | 272 ± 32 |
| Right | 6 | 3 | 268 ± 56 | 391 ± 96 | 420 ± 114 |
| Right | 6 | 4 | 287 ± 92 | 400 ± 122 | 457 ± 141 |
| Right | 6 | 5 | 290 ± 56 | 421 ± 133 | 500 ± 166 |
| Right | 6 | 6 | 276 ± 55 | 422 ± 135 | 466 ± 121 |

Table 5.10. Mean RT by ID.

| Hand | Number of Targets | Opposite Index of Difficulty | Mean and Std for Reaction Time (msec) ID = 3 | ID = 4 | ID = 5 | ID = 6 |
|---|---|---|---|---|---|---|
| Left | 1 | None | 218 ± 28 | 220 ± 22 | 235 ± 29 | 241 ± 33 |
| Left | 1 | 3 | 236 ± 25 | 245 ± 29 | 251 ± 35 | 267 ± 48 |
| Left | 1 | 4 | 244 ± 32 | 258 ± 56 | 264 ± 41 | 275 ± 65 |
| Left | 1 | 5 | 251 ± 57 | 256 ± 46 | 275 ± 47 | 269 ± 36 |
| Left | 1 | 6 | 267 ± 64 | 265 ± 57 | 281 ± 48 | 272 ± 49 |
| Left | 2 | None | 233 ± 27 | 238 ± 25 | 253 ± 37 | 255 ± 39 |
| Left | 2 | 3 | 333 ± 85 | 337 ± 97 | 351 ± 79 | 372 ± 111 |
| Left | 2 | 4 | 336 ± 85 | 343 ± 117 | 379 ± 117 | 379 ± 107 |
| Left | 2 | 5 | 353 ± 94 | 367 ± 129 | 403 ± 110 | 405 ± 129 |
| Left | 2 | 6 | 365 ± 93 | 382 ± 149 | 430 ± 204 | 461 ± 163 |
| Left | 4 | None | 250 ± 31 | 253 ± 37 | 268 ± 44 | 268 ± 39 |
| Left | 4 | 3 | 389 ± 90 | 393 ± 103 | 425 ± 116 | 436 ± 129 |
| Left | 4 | 4 | 376 ± 112 | 392 ± 112 | 461 ± 119 | 428 ± 134 |
| Left | 4 | 5 | 424 ± 174 | 426 ± 168 | 509 ± 201 | 513 ± 171 |
| Left | 4 | 6 | 424 ± 192 | 391 ± 109 | 495 ± 194 | 524 ± 170 |
| Right | 1 | None | 217 ± 26 | 220 ± 27 | 232 ± 24 | 237 ± 30 |
| Right | 1 | 3 | 238 ± 27 | 244 ± 33 | 250 ± 38 | 268 ± 56 |
| Right | 1 | 4 | 248 ± 29 | 259 ± 50 | 268 ± 46 | 287 ± 92 |
| Right | 1 | 5 | 249 ± 31 | 255 ± 43 | 273 ± 50 | 290 ± 56 |
| Right | 1 | 6 | 270 ± 44 | 259 ± 31 | 274 ± 61 | 276 ± 55 |
| Right | 2 | None | 247 ± 31 | 252 ± 42 | 256 ± 33 | 264 ± 44 |
| Right | 2 | 3 | 339 ± 82 | 328 ± 65 | 365 ± 93 | 391 ± 96 |
| Right | 2 | 4 | 336 ± 89 | 332 ± 74 | 396 ± 129 | 400 ± 122 |
| Right | 2 | 5 | 348 ± 67 | 366 ± 105 | 431 ± 125 | 421 ± 133 |
| Right | 2 | 6 | 343 ± 78 | 353 ± 79 | 394 ± 103 | 422 ± 135 |
| Right | 4 | None | 257 ± 33 | 265 ± 40 | 276 ± 40 | 272 ± 32 |
| Right | 4 | 3 | 378 ± 68 | 371 ± 75 | 438 ± 127 | 420 ± 114 |
| Right | 4 | 4 | 385 ± 106 | 400 ± 108 | 452 ± 128 | 457 ± 141 |
| Right | 4 | 5 | 428 ± 148 | 400 ± 92 | 530 ± 158 | 500 ± 166 |
| Right | 4 | 6 | 441 ± 156 | 429 ± 175 | 505 ± 149 | 466 ± 121 |

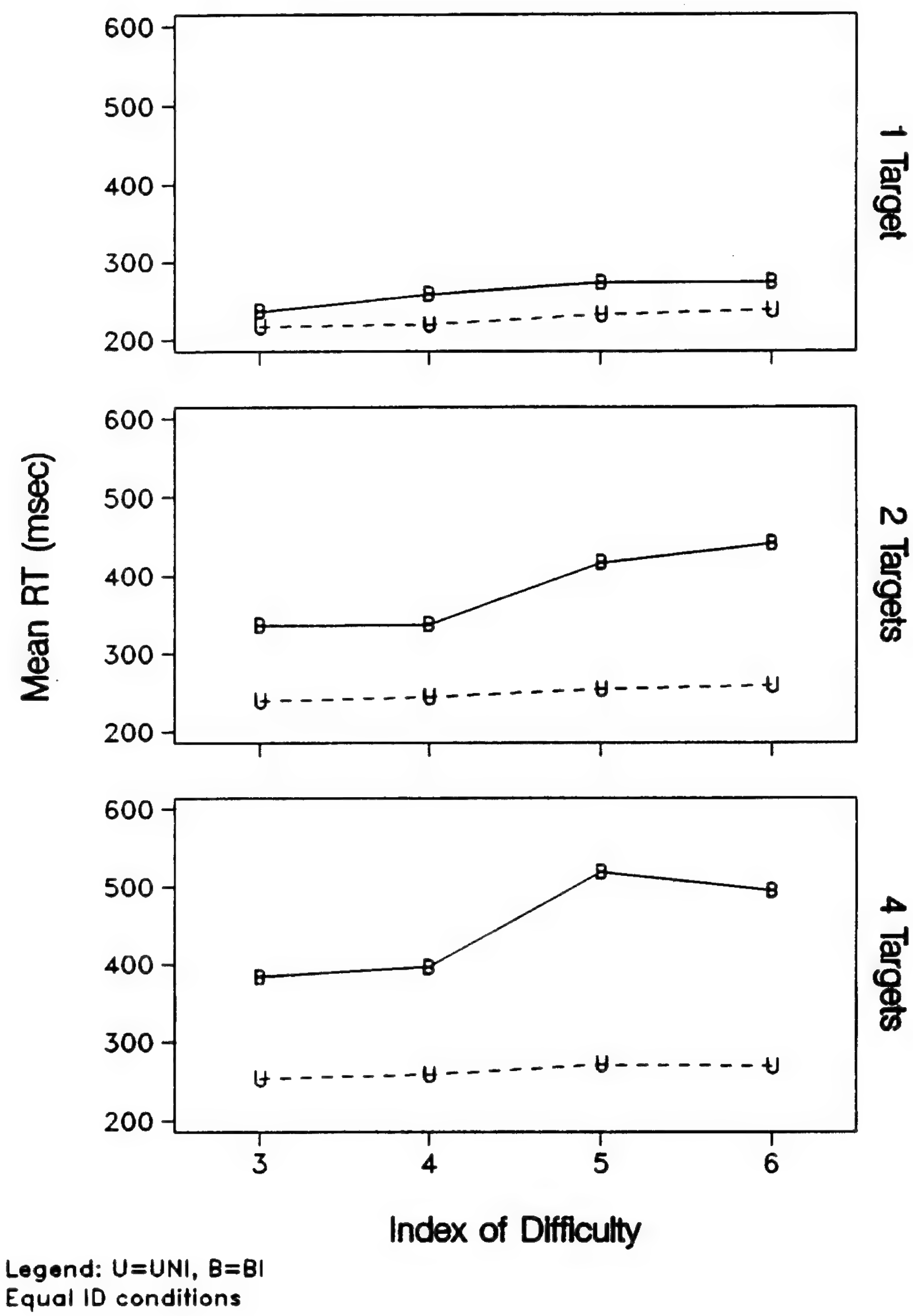



Figure 5.2. Unimanual-Bimanual Comparison of RT vs. ID by N.

Table 5.11. Unimanual RT and MT ANOVA.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, UNIMANUAL CONDITION

INDEPENDENT VARIABLES

HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 3291 | 18 | 8122 | 7.29 | 0.0146 |
| ID | 3 | 29155 | 54 | 24087 | 21.79 | 0.0001 |
| TARGETS | 2 | 102856 | 36 | 27725 | 66.78 | 0.0001 |
| HAND*ID | 3 | 768 | 54 | 16878 | 0.82 | 0.4891 |
| HAND*TARGETS | 2 | 2912 | 36 | 10846 | 4.83 | 0.0138 |
| ID*TARGETS | 6 | 870 | 108 | 20299 | 0.77 | 0.5941 |
| HAND*ID*TARGETS | 6 | 458 | 108 | 21005 | 0.39 | 0.8826 |

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, UNIMANUAL CONDITION

INDEPENDENT VARIABLES

HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 156381 | 18 | 54799 | 51.37 | 0.0001 |
| ID | 3 | 4422123 | 54 | 130065 | 611.99 | 0.0001 |
| TARGETS | 2 | 67313 | 36 | 37775 | 32.07 | 0.0001 |
| HAND*ID | 3 | 8968 | 54 | 52455 | 3.08 | 0.0351 |
| HAND*TARGETS | 2 | 1065 | 36 | 30478 | 0.63 | 0.5389 |
| ID*TARGETS | 6 | 7670 | 108 | 86087 | 1.60 | 0.1530 |
| HAND*ID*TARGETS | 6 | 3699 | 108 | 80595 | 0.83 | 0.5521 |

The significance of the number of target alternatives was expected from Hick's Law and was very strong under these conditions. The ID effect was also very strong and suggests that, under the conditions tested, RT is also a function of the task movement difficulty. A significant HAND effect was expected. However, the direction of the effect was opposite the expectation since all subjects were right-hand dominant. Kelso et al. (1979) obtained similar results. The HAND x N interaction suggests that the RT difference between hands was not constant across the varying number of target alternatives. Appendix F presents unimanual left hand and right hand mean RTs for all conditions.

To compare results with Fowler et al. (1991), a 2 x 2 x 4 x 3 repeated measures analysis of variance (COND x N x ID x HAND) was conducted on the combined unimanual and bimanual equal-ID RT data treating subjects as a random factor (Table 5.12). COND (unimanual vs. bimanual) was significant, $F(1,8) = 94.34$, $p = 0.0001$, with the unimanual reactions faster (247 vs. 364 msec). The number of target alternatives was significant, $F(2,36) = 123.26$, $p \leq 0.0001$. RT increased with increasing N. ID was significant $F(3,54) = 38.20$, $p \leq 0.0001$, with slower RTs associated with higher IDs. Neither HAND nor any interactions with HAND were significant. All other interactions were statistically significant with $p \leq 0.0001$. Figure 5.2 presents RT as a function of ID for the one, two, and four target alternative levels. For a given level of N, notice that as ID increases, the difference between the bimanual and unimanual conditions increases. Notice too, that as the number of target alternatives increases, this difference is more pronounced.

Table 5.12. RT ANOVA for Bimanual Equal-ID Task.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, EQUAL ID CONDITIONS

INDEPENDENT VARIABLES

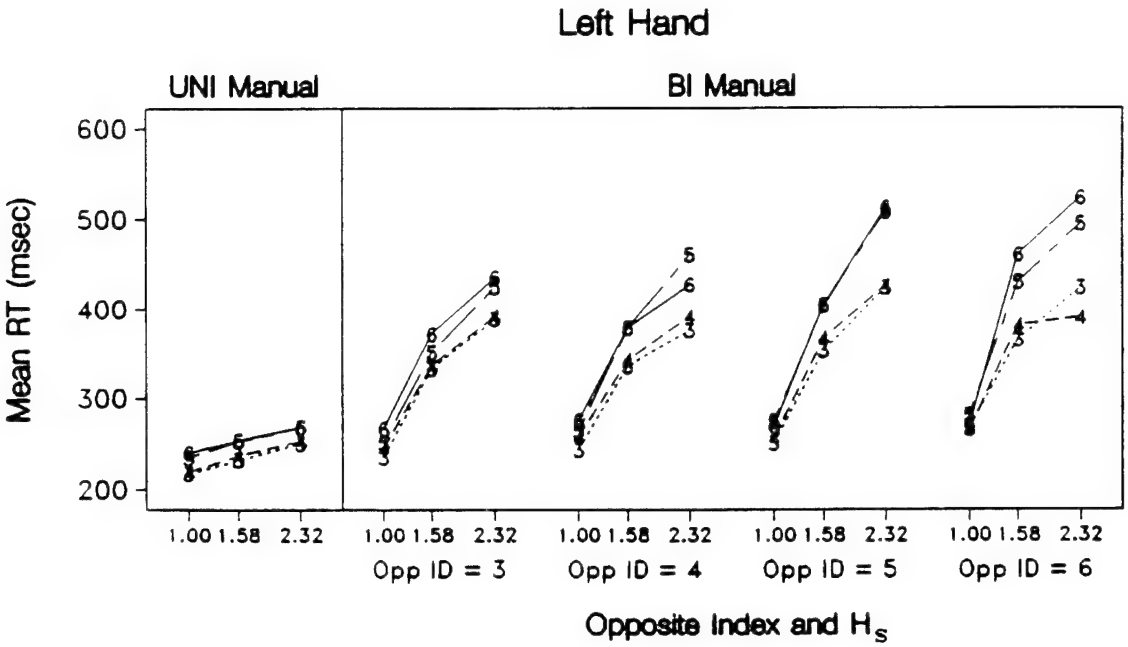
CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 3127296 | 18 | 596668 | 94.34 | 0.0001 |
| HAND | 1 | 74 | 18 | 98183 | 0.01 | 0.9088 |
| ID | 3 | 513724 | 54 | 242072 | 38.20 | 0.0001 |
| TARGETS | 2 | 1962059 | 36 | 286517 | 123.26 | 0.0001 |
| COND*HAND | 1 | 5264 | 18 | 124854 | 0.76 | 0.3952 |
| COND*ID | 3 | 228424 | 54 | 178936 | 22.98 | 0.0001 |
| HAND*ID | 3 | 16779 | 54 | 167333 | 1.80 | 0.1572 |
| COND*TARGETS | 2 | 898066 | 36 | 189827 | 85.16 | 0.0001 |
| HAND*TARGETS | 2 | 696 | 36 | 76752 | 0.16 | 0.8500 |
| ID*TARGETS | 6 | 95411 | 108 | 210231 | 8.17 | 0.0001 |
| COND*HAND*ID | 3 | 15605 | 54 | 175733 | 1.60 | 0.2005 |
| COND*HAND*TARGETS | 2 | 4718 | 36 | 89238 | 0.95 | 0.3956 |
| COND*ID*TARGETS | 6 | 100987 | 108 | 192745 | 9.43 | 0.0001 |
| HAND*ID*TARGETS | 6 | 12277 | 108 | 167396 | 1.32 | 0.2544 |
| COND*HAND*ID*TARGETS | 6 | 12547 | 108 | 172038 | 1.31 | 0.2576 |

Figure 5.3 presents mean RT vs. $H_s$ for the unimanual and bimanual conditions by hand and by opposite hand ID (OPID). Figure 5.4 presents mean RT vs. index of difficulty for the unimanual and bimanual conditions by hand and by OPID. See Appendix F for mean RTs for all combinations of conditions tested. Separate repeated measures ANOVAs were conducted on the RT data for each of the levels of N (Table 5.13). COND, ID and the COND x ID interaction were all significant for N = 1, 2 and 4.

As illustrated in Figure 5.3, both the left and right hands behaved similarly under the unimanual conditions. The left hand results appeared to be especially linear. Under bimanual conditions, RT behavior changes were quite evident. Some linearity was lost compared to the unimanual case due mostly to the change in slope from the two to four target case. That is, a greater increase in RT occurred from the N = 1 to N = 2 condition than from the N = 2 to the N = 4 condition. This effect was also seen in Figure 5.4 where a larger difference was noted between the N = 1 and the N = 2 condition than between the N = 2 and the N = 4 condition.

For the unimanual condition, Figure 5.4 shows an upward trend in RT as ID increased. A shift upward also occurred as the number of target alternatives increased. Reaction time clearly increased as the contralateral limb movement was added. There were clear RT differences between the different levels of N for both the left and right hands. Notice that the N = 1 bimanual conditions for all OPID are not too different in behavior from the unimanual conditions. However, as soon as the number of target alternatives was two or greater, very large RT differences occurred between the unimanual and bimanual tasks.



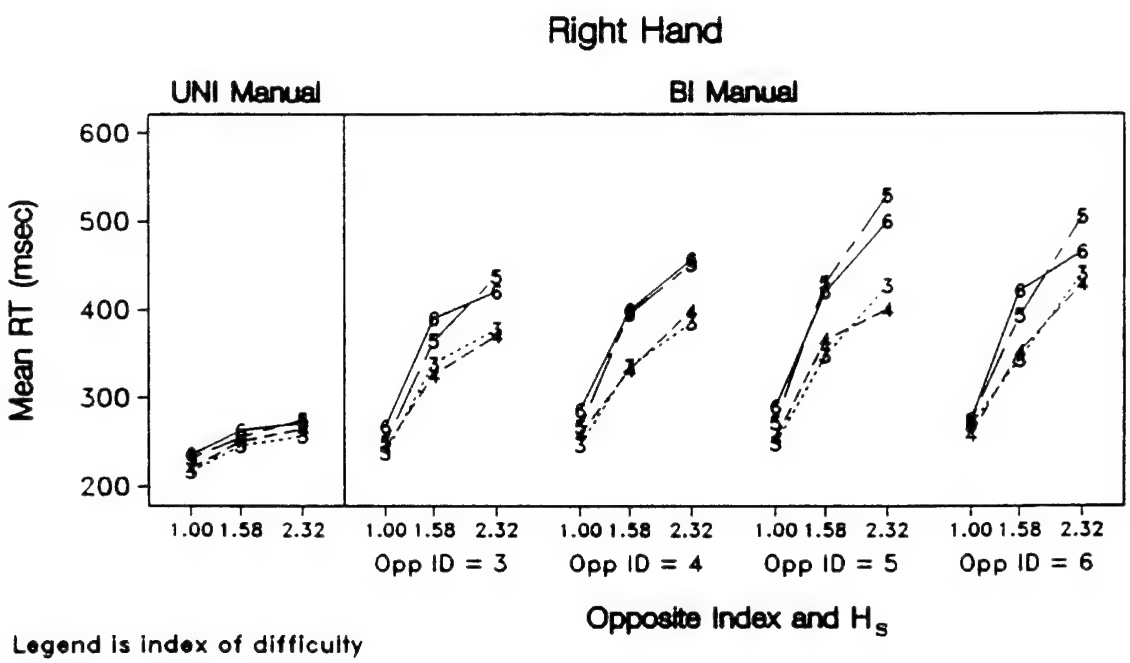




Figure 5.3. Mean RT vs. Stimulus Information by ID, OPID and HAND.

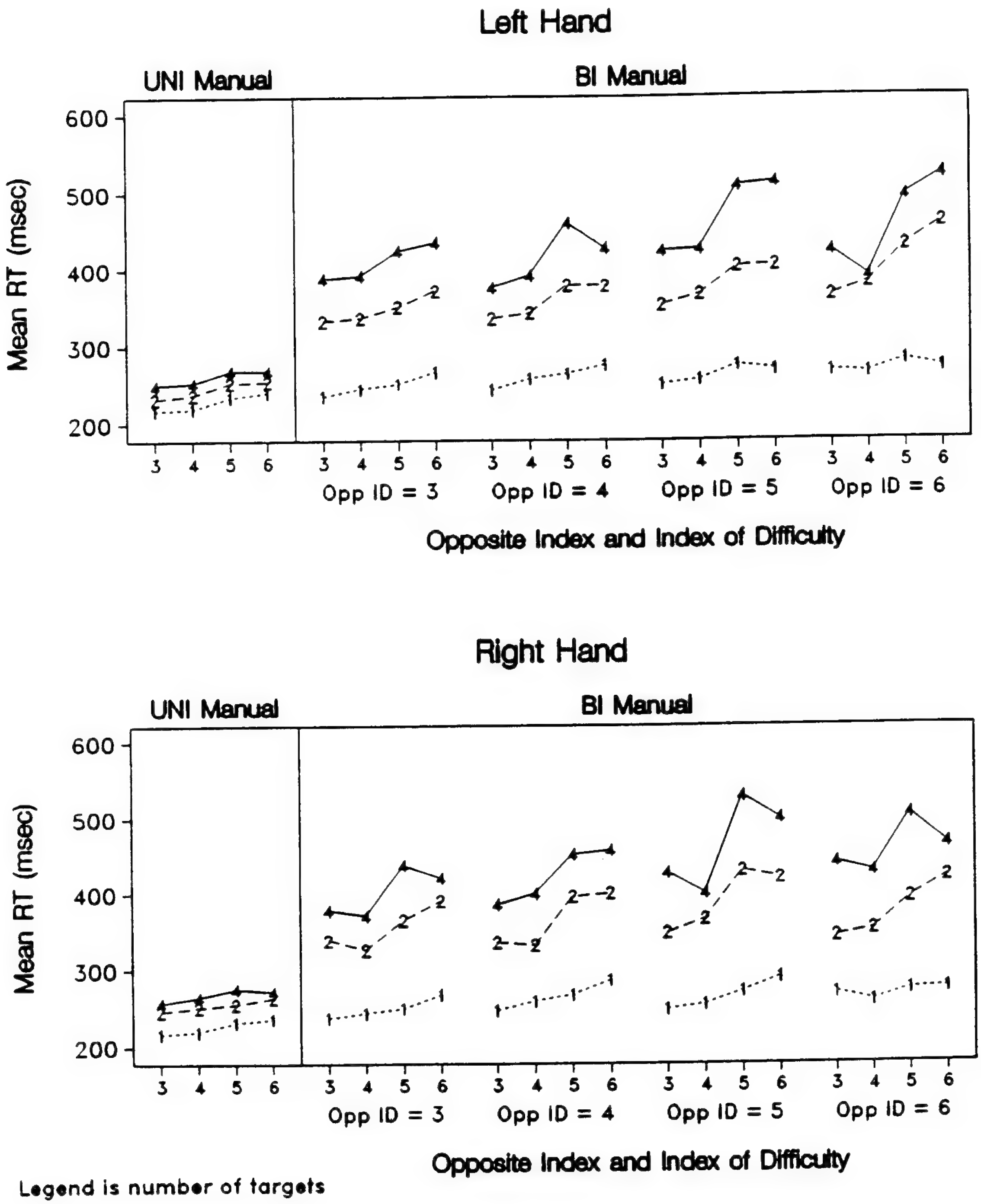



Figure 5.4. Mean RT vs. ID by N, OPID and HAND.

Table 5.13. RT ANOVA by Target Alternative Levels.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, EQUAL ID CONDITIONS BY TARGET

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6

TARGETS=1

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 84990 | 18 | 33618 | 45.51 | 0.0001 |
| HAND | 1 | 0 | 18 | 4521 | 0.00 | 0.9858 |
| ID | 3 | 41748 | 54 | 55438 | 13.55 | 0.0001 |
| COND*HAND | 1 | 188 | 18 | 2082 | 1.62 | 0.2187 |
| COND*ID | 3 | 5092 | 54 | 28397 | 3.23 | 0.0295 |
| HAND*ID | 3 | 143 | 54 | 6291 | 0.41 | 0.7470 |
| COND*HAND*ID | 3 | 186 | 54 | 8565 | 0.39 | 0.7601 |

TARGETS=2

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 1350822 | 18 | 339380 | 71.64 | 0.0001 |
| HAND | 1 | 659 | 18 | 33556 | 0.35 | 0.5596 |
| ID | 3 | 226548 | 54 | 181099 | 22.52 | 0.0001 |
| COND*HAND | 1 | 4006 | 18 | 52173 | 1.38 | 0.2551 |
| COND*ID | 3 | 117771 | 54 | 158823 | 13.35 | 0.0001 |
| HAND*ID | 3 | 9577 | 54 | 91369 | 1.89 | 0.1428 |
| COND*HAND*ID | 3 | 13339 | 54 | 100965 | 2.38 | 0.0799 |

TARGETS=4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 2589550 | 18 | 413496 | 112.73 | 0.0001 |
| HAND | 1 | 111 | 18 | 136858 | 0.01 | 0.9053 |
| ID | 3 | 340839 | 54 | 215766 | 28.43 | 0.0001 |
| COND*HAND | 1 | 5788 | 18 | 159837 | 0.65 | 0.4300 |
| COND*ID | 3 | 206548 | 54 | 184462 | 20.16 | 0.0001 |
| HAND*ID | 3 | 19336 | 54 | 237069 | 1.47 | 0.2335 |
| COND*HAND*ID | 3 | 14627 | 54 | 238241 | 1.11 | 0.3551 |

### 5.3.3 RT - Bimanual Equal-ID vs. Unequal-ID

Appendix G presents the mean RT data for all conditions tested. Generally, as OPID increased, RT increased over the bimanual equal-ID condition. Figure 5.5 presents mean RT as a function of OPID by N. Notice the large increase from the $N = 1$ to the $N = 2$ condition compared to the increase from $N = 2$ to $N = 4$. Also notice the OPID x N interaction.

Repeated measures ANOVAs treating subjects as a random factor were conducted on the RT data (Table 5.14) at each ID (3, 4, 5, 6) to compare bimanual equal-ID and the bimanual unequal-ID performance. Statistical significance was found for the number of target alternatives ($p = 0.0001$) and for OPID ($p = 0.0002$) at each ID level. In addition, significant OPID x N interactions existed at ID = 5 and 6 ($p \leq 0.05$).

Contrasts showed (Table 5.15, $\alpha = 0.05$) that OPIDs 3 and 4 were paired and that OPIDs 5 and 6 were paired. That is, at ID = 3, OPID = 3 and 4 were paired, OPID 5 and 4 were paired, and OPIDs 5 and 6 were paired. At ID = 4, OPIDs 4, 5, and 6 were paired, and OPIDs 3 and 4 were paired. At ID = 5, OPIDs 3 and 4; 4 and 6; and 5 and 6 were paired. At ID = 6, OPIDs 3 and 4; and 5 and 6 were paired. These results suggest that reaction times were similar when the opposite hand was performing a task that was nearly equivalent in ID (e.g., a 3-4 pair or a 5-6 pair). But, when OPID differed by more than one, significant reaction time differences occurred. Contrasts showed all target alternative levels to be significantly different (Table 5.16, $\alpha = 0.05$).

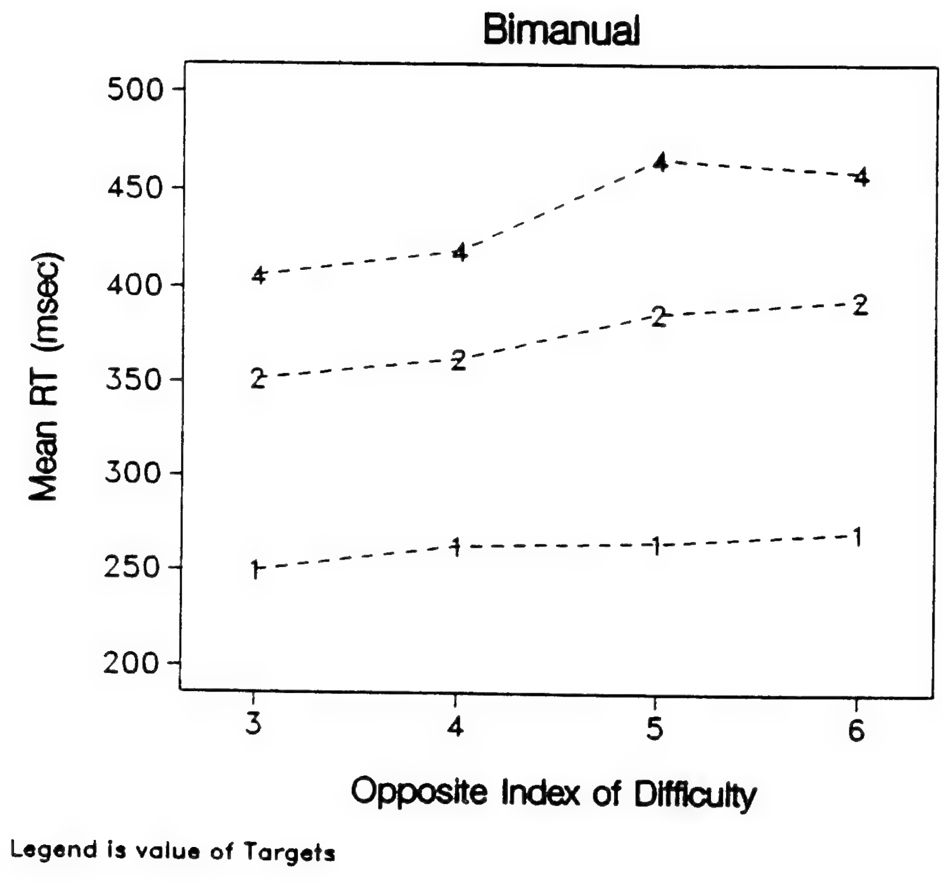



Figure 5.5. RT vs. OPID by N.

Table 5.14. RT ANOVA Equal-ID vs. Unequal-ID by ID.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

INDEPENDENT VARIABLES

HAND: LEFT, RIGHT
OPPOSITE INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

INDEX OF DIFFICULTY=3

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 27 | 18 | 81068 | 0.01 | 0.9397 |
| OPPOSITE | 3 | 88929 | 54 | 205077 | 7.81 | 0.0002 |
| TARGETS | 2 | 1862545 | 36 | 675052 | 49.66 | 0.0001 |
| HAND*OPPOSITE | 3 | 550 | 54 | 64141 | 0.15 | 0.9264 |
| HAND*TARGETS | 2 | 2025 | 36 | 44630 | 0.82 | 0.4499 |
| OPPOSITE*TARGETS | 6 | 26489 | 108 | 308191 | 1.55 | 0.1698 |
| HAND*OPPOSIT*TARGETS | 6 | 7488 | 108 | 106124 | 1.27 | 0.2772 |

INDEX OF DIFFICULTY=4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 2868 | 18 | 282426 | 0.18 | 0.6741 |
| OPPOSITE | 3 | 57340 | 54 | 237331 | 4.35 | 0.0081 |
| TARGETS | 2 | 1652611 | 36 | 394424 | 75.42 | 0.0001 |
| HAND*OPPOSITE | 3 | 3166 | 54 | 149010 | 0.38 | 0.7660 |
| HAND*TARGETS | 2 | 3691 | 36 | 218447 | 0.30 | 0.7396 |
| OPPOSITE*TARGETS | 6 | 13696 | 108 | 303802 | 0.81 | 0.5632 |
| HAND*OPPOSIT*TARGETS | 6 | 26506 | 108 | 268794 | 1.78 | 0.1109 |

Table 5.14. RT ANOVA Equal-ID vs. Unequal-ID by ID (cont.).

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

INDEPENDENT VARIABLES

HAND: LEFT, RIGHT
OPPOSITE INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

INDEX OF DIFFICULTY=5

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 1981 | 18 | 401620 | 0.09 | 0.7691 |
| OPPOSITE | 3 | 231059 | 54 | 422447 | 9.85 | 0.0001 |
| TARGETS | 2 | 3394211 | 36 | 649425 | 94.08 | 0.0001 |
| HAND*OPPOSITE | 3 | 10660 | 54 | 165463 | 1.16 | 0.3337 |
| HAND*TARGETS | 2 | 2033 | 36 | 347600 | 0.11 | 0.9003 |
| OPPOSITE*TARGETS | 6 | 51605 | 108 | 399051 | 2.33 | 0.0375 |
| HAND*OPPOSIT*TARGETS | 6 | 17296 | 108 | 336228 | 0.93 | 0.4794 |

INDEX OF DIFFICULTY=6

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 3 | 18 | 327816 | 0.00 | 0.9903 |
| OPPOSITE | 3 | 161371 | 54 | 278745 | 10.42 | 0.0001 |
| TARGETS | 2 | 2936714 | 36 | 583869 | 90.54 | 0.0001 |
| HAND*OPPOSITE | 3 | 40844 | 54 | 474793 | 1.55 | 0.2126 |
| HAND*TARGETS | 2 | 11833 | 36 | 110330 | 1.93 | 0.1598 |
| OPPOSITE*TARGETS | 6 | 94907 | 108 | 419780 | 4.07 | 0.0010 |
| HAND*OPPOSIT*TARGETS | 6 | 21111 | 108 | 280355 | 1.36 | 0.2393 |

Table 5.15. OPID Contrasts.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

PAIRWISE COMPARISON OF OPPOSITE INDEX OF DIFFICULTY FOR EACH INDEX OF DIFFICULTY

| ID | MSD(TUKEY) | OPPID LEVEL 1 | OPPID LEVEL 2 | MEAN LEVEL 1 | MEAN LEVEL 2 | MEAN DIFF | SIGNIFICANTLY DIFFERENT |
|---|---|---|---|---|---|---|---|
| 3 | 21.6 | 3 | 4 | 318.8 | 320.8 | 2.1 | |
| 3 | 21.6 | 3 | 5 | 318.8 | 342.1 | 23.3 | * |
| 3 | 21.6 | 3 | 6 | 318.8 | 351.7 | 32.9 | * |
| 3 | 21.6 | 4 | 5 | 320.8 | 342.1 | 21.2 | |
| 3 | 21.6 | 4 | 6 | 320.8 | 351.7 | 30.8 | * |
| 3 | 21.6 | 5 | 6 | 342.1 | 351.7 | 9.6 | |
| 4 | 23.3 | 3 | 4 | 319.3 | 330.6 | 11.4 | |
| 4 | 23.3 | 3 | 5 | 319.3 | 345.4 | 26.1 | * |
| 4 | 23.3 | 3 | 6 | 319.3 | 346.4 | 27.1 | * |
| 4 | 23.3 | 4 | 5 | 330.6 | 345.4 | 14.7 | |
| 4 | 23.3 | 4 | 6 | 330.6 | 346.4 | 15.8 | |
| 4 | 23.3 | 5 | 6 | 345.4 | 346.4 | 1.0 | |
| 5 | 31.1 | 3 | 4 | 346.6 | 369.9 | 23.2 | |
| 5 | 31.1 | 3 | 5 | 346.6 | 403.3 | 56.7 | * |
| 5 | 31.1 | 3 | 6 | 346.6 | 396.5 | 49.8 | * |
| 5 | 31.1 | 4 | 5 | 369.9 | 403.3 | 33.4 | * |
| 5 | 31.1 | 4 | 6 | 369.9 | 396.5 | 26.6 | |
| 5 | 31.1 | 5 | 6 | 403.3 | 396.5 | -6.8 | |
| 6 | 25.2 | 3 | 4 | 359.0 | 370.9 | 11.9 | |
| 6 | 25.2 | 3 | 5 | 359.0 | 399.7 | 40.7 | * |
| 6 | 25.2 | 3 | 6 | 359.0 | 403.4 | 44.4 | * |
| 6 | 25.2 | 4 | 5 | 370.9 | 399.7 | 28.8 | * |
| 6 | 25.2 | 4 | 6 | 370.9 | 403.4 | 32.5 | * |
| 6 | 25.2 | 5 | 6 | 399.7 | 403.4 | 3.7 | |

Table 5.16. Target Alternative Level Contrasts.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR REACTION TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

PAIRWISE COMPARISON OF TARGETS FOR EACH INDEX OF DIFFICULTY

| ID | MSD(TUKEY) | TARGETS LEVEL 1 | TARGETS LEVEL 2 | MEAN LEVEL 1 | MEAN LEVEL 2 | MEAN DIFF | SIGNIFICANTLY DIFFERENT |
|---|---|---|---|---|---|---|---|
| 3 | 38.4 | 1 | 2 | 250.2 | 344.2 | 94.0 | * |
| 3 | 38.4 | 1 | 4 | 250.2 | 405.6 | 155.4 | * |
| 3 | 38.4 | 2 | 4 | 344.2 | 405.6 | 61.4 | * |
| 4 | 29.4 | 1 | 2 | 255.2 | 350.7 | 95.5 | * |
| 4 | 29.4 | 1 | 4 | 255.2 | 400.3 | 145.1 | * |
| 4 | 29.4 | 2 | 4 | 350.7 | 400.3 | 49.6 | * |
| 5 | 37.7 | 1 | 2 | 267.0 | 393.5 | 126.5 | * |
| 5 | 37.7 | 1 | 4 | 267.0 | 476.8 | 209.9 | * |
| 5 | 37.7 | 2 | 4 | 393.5 | 476.8 | 83.3 | * |
| 6 | 35.7 | 1 | 2 | 275.5 | 406.2 | 130.7 | * |
| 6 | 35.7 | 1 | 4 | 275.5 | 468.0 | 192.5 | * |
| 6 | 35.7 | 2 | 4 | 406.2 | 468.0 | 61.9 | * |

Simple regressions of RT on stimulus information ($H_s$) are shown in Figures 5.6 through 5.10. Each figure shows the RT relationship for OPID, including the OPID = "none" (unimanual) task for the four task IDs shown at the right. Each plot is given for the left and right hands and for the index of difficulty of that hand. For example, the top left graph of Figure 5.6 plots the regression of RT on $H_s$ for the left hand, unimanual, ID = 3 task. The bottom right graph of Figure 5.7 plots the regression of RT on $H_s$ for the right hand, bimanual, ID = 6 task with the left hand performing at ID = 3 (OPID = 3). The coefficient of determination ($R^2$) value for each regression is given in the upper left corner of each graph as well as the slope of the regression line and the mean value.

Post-hoc tests confirmed that all slopes were different from zero ($p \leq 0.0001$) for the left and right hands and for each ID and OPID. Post-hoc analyses on slopes showed no significance for OPID = 3 vs. OPID = 4 and for OPID = 5 vs. OPID = 6 ($p = 0.9996$ and $p = 0.1453$ respectively). Slope differences between the four bimanual opposite ID conditions and the unimanual condition were all significant (Figure 5.11).

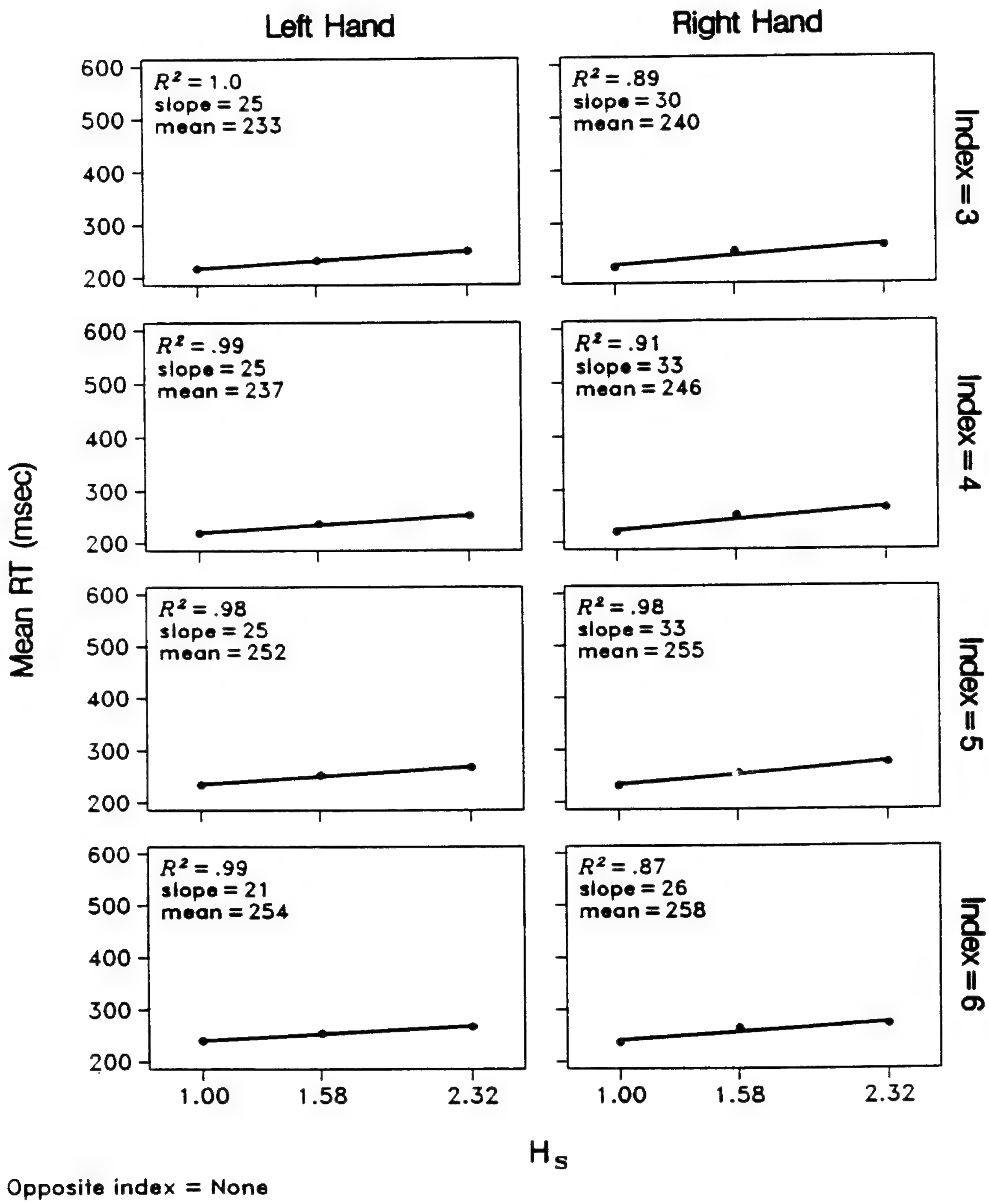



Figure 5.6. RT Regressed on H (OPID = None).

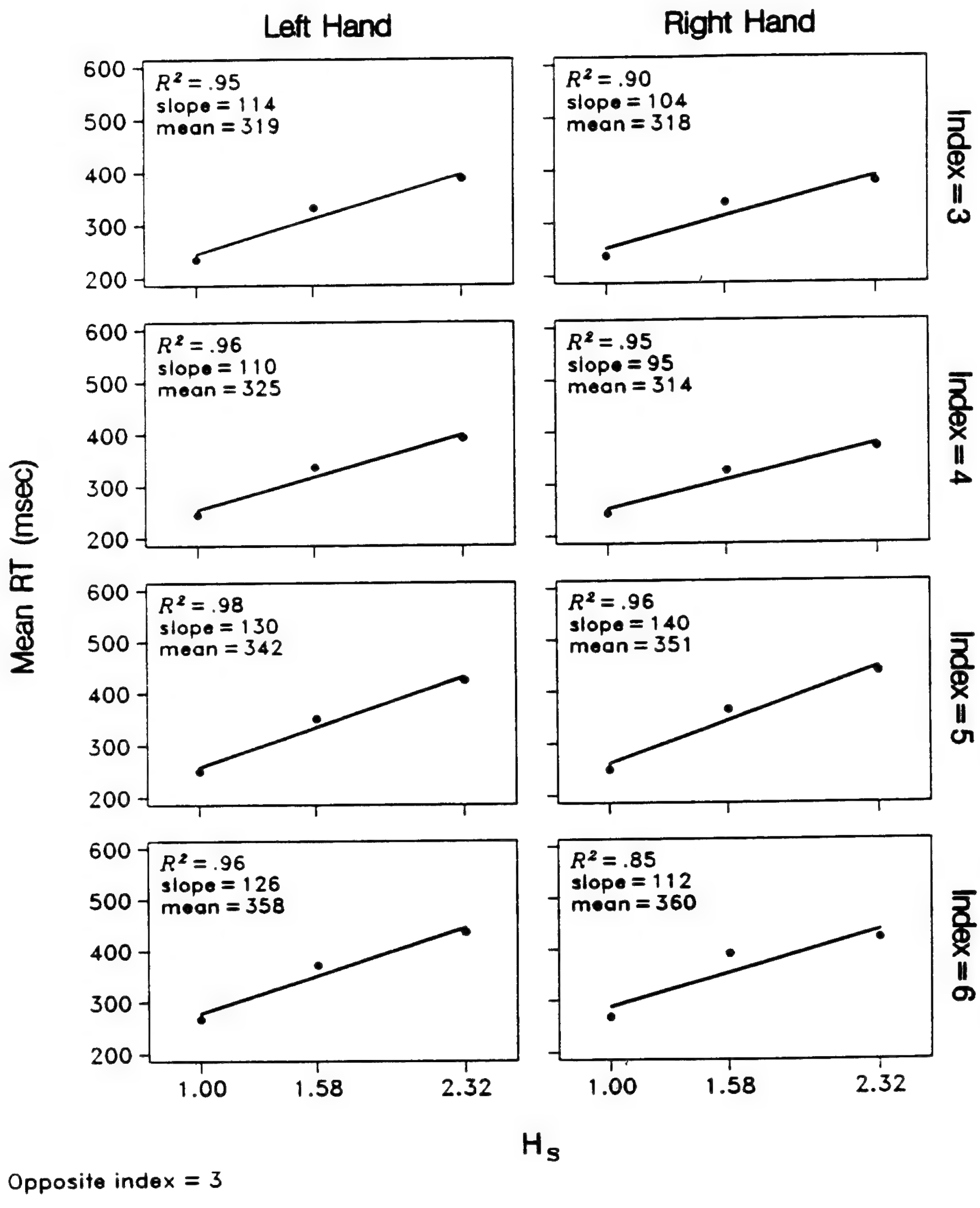



Figure 5.7. RT Regressed on H (OPID = 3).

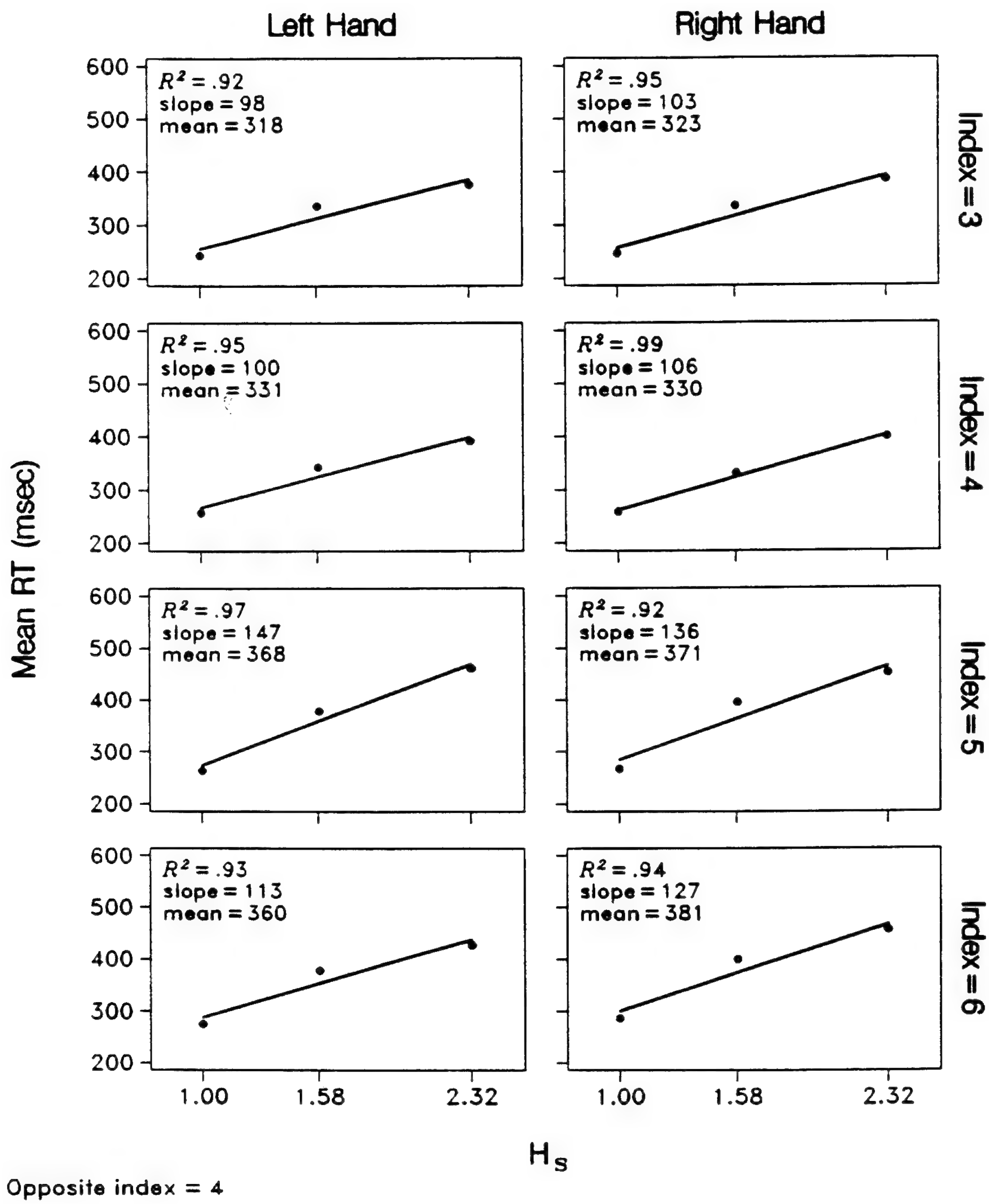



Figure 5.8. RT Regressed on H (OPID = 4).

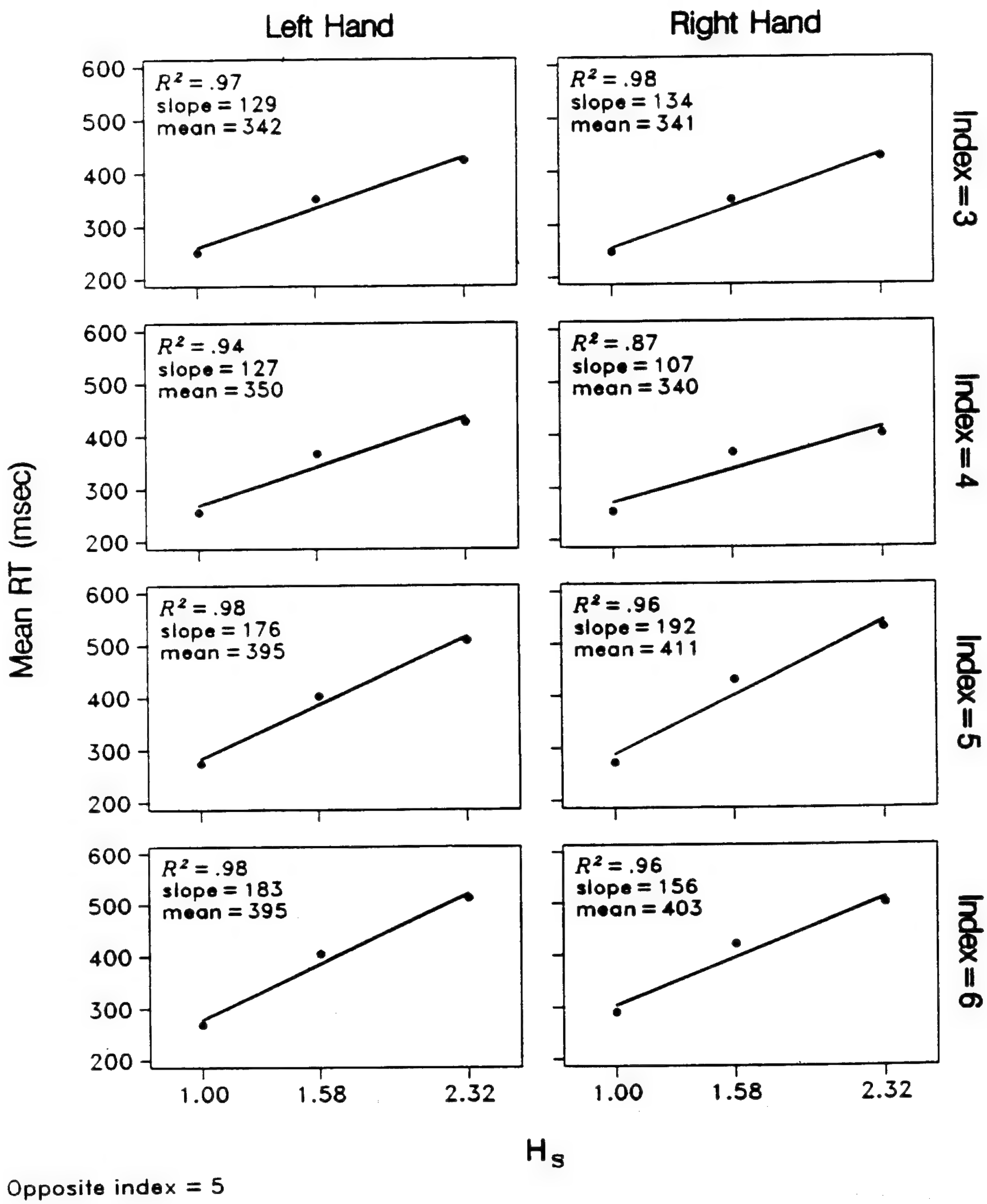



Figure 5.9. RT Regressed on H (OPID = 5).

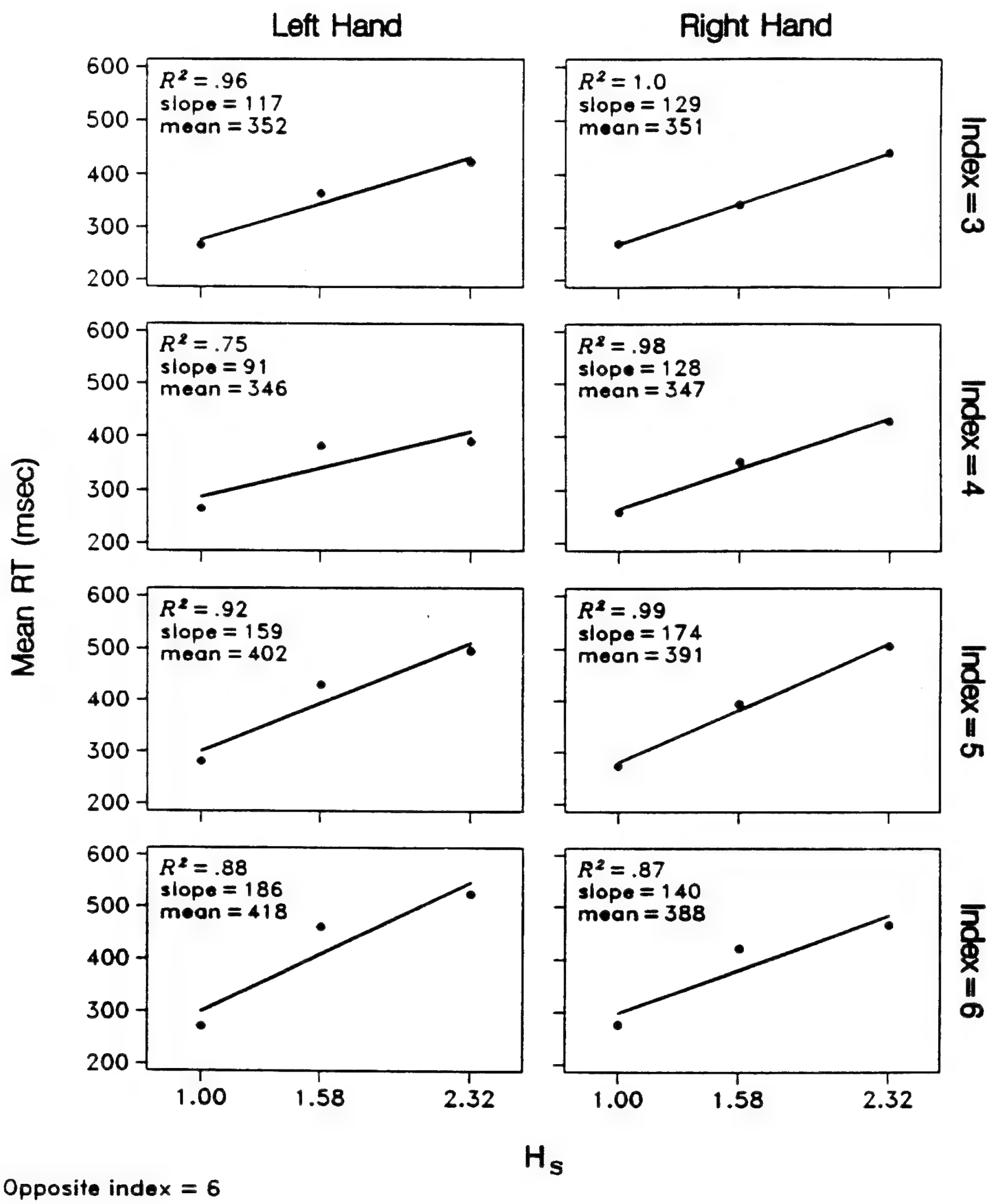



Figure 5.10. RT Regressed on H (OPID = 6).

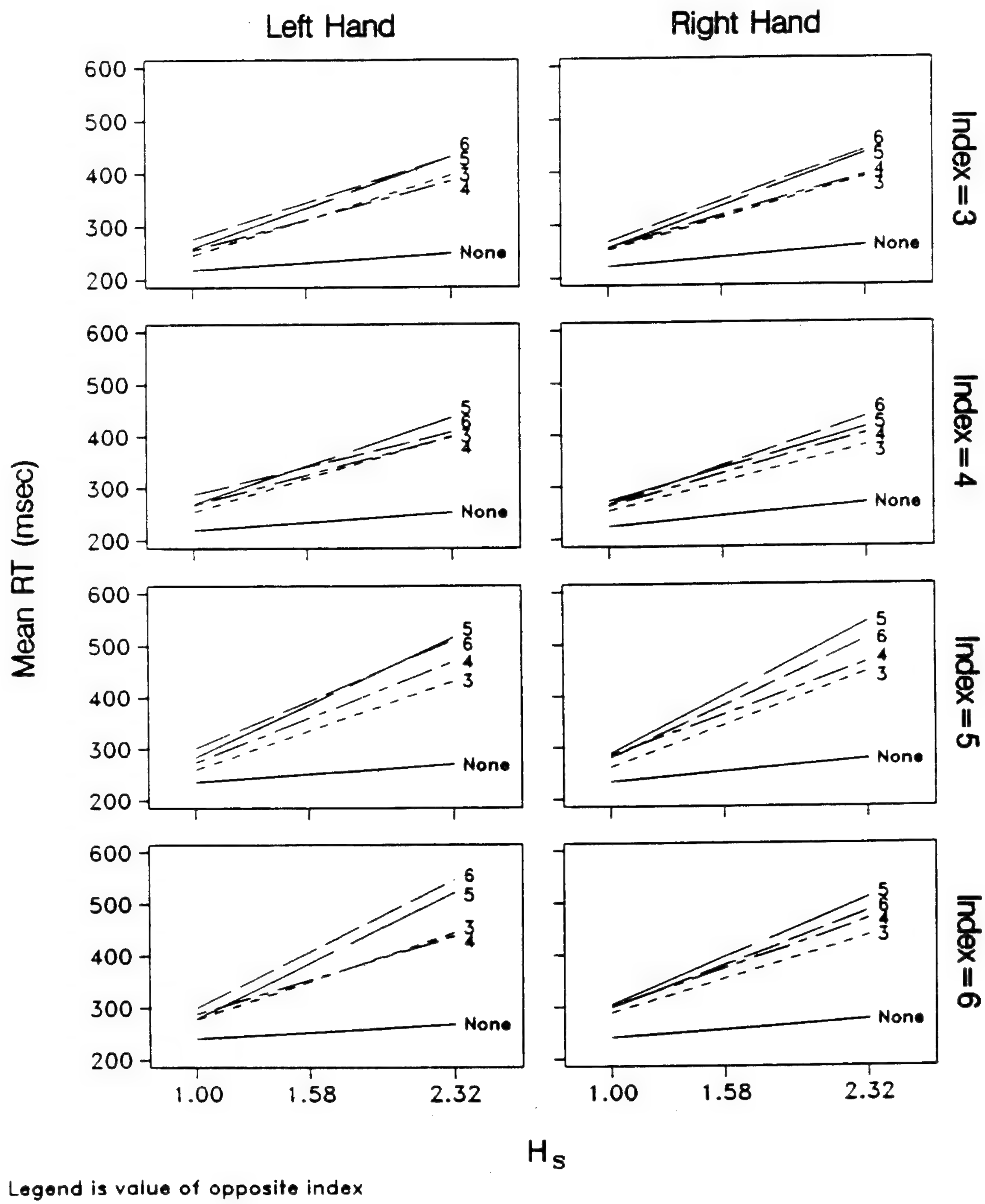



Figure 5.11. RT Regressed on H - Comparing OPID by Hand.

### 5.3.4 MT - Unimanual and Bimanual Equal-ID

Table 5.17 presents the means and standard deviations for MT as a function of ID for all conditions. Figure 5.12 presents mean MT as a function of ID for N = 1, 2 and 4. Figure 5.13 presents unimanual and bimanual MT as a function of ID by OPID for the left and right hands. First, movement time data were analyzed for main effects and then, by comparing unimanual and bimanual equal-ID conditions. Finally, bimanual equal-ID and bimanual unequal-ID conditions were compared.

Movement time results can be compared with Methods Time Measurement (MTM) tables (Antis, Honeycutt, and Koch, 1986). Using MTM tables for a Reach, and Cases B and D (reach with medium control and reach with high control), 8-inch movement times (IDs = 3 and 4) were expected to range between 363 and 414 milliseconds. Sixteen-inch movements (IDs = 5 and 6) were expected to fall between 569 and 612 milliseconds. From Table 5.17, experimental results for ID = 3 and ID = 4 yielded average movement times of 211 to 538 milliseconds. For ID = 5 and 6, movement times ranged from 353 to 858 milliseconds. Therefore, the range of mean MT values obtained in this study fell outside the range predicted by the MTM tables for similar movements.

Unimanual movement time data were analyzed using a 2 x 4 x 3 repeated measures ANOVA (N x ID x HAND) treating subjects as a random factor (Table 5.11). There were three significant main effects on MT. The number of target alternatives was significant, $F(2,36) = 32.07$, $p \leq 0.0001$, with MT increasing as the number of target

Table 5.17. Mean MT by ID.

| Hand | Number of Targets | Opposite Index of Difficulty | Mean and Std for Movement Time (msec) ID = 3 | ID = 4 | ID = 5 | ID = 6 |
|---|---|---|---|---|---|---|
| Left | 1 | None | 251 ± 53 | 290 ± 54 | 379 ± 62 | 510 ± 72 |
| Left | 1 | 3 | 279 ± 66 | 346 ± 82 | 446 ± 91 | 549 ± 91 |
| Left | 1 | 4 | 303 ± 57 | 377 ± 121 | 565 ± 126 | 595 ± 94 |
| Left | 1 | 5 | 363 ± 79 | 456 ± 101 | 598 ± 117 | 664 ± 139 |
| Left | 1 | 6 | 415 ± 110 | 487 ± 139 | 663 ± 161 | 768 ± 163 |
| Left | 2 | None | 258 ± 54 | 305 ± 55 | 417 ± 71 | 523 ± 71 |
| Left | 2 | 3 | 323 ± 56 | 405 ± 73 | 536 ± 67 | 612 ± 88 |
| Left | 2 | 4 | 372 ± 66 | 461 ± 65 | 609 ± 91 | 687 ± 99 |
| Left | 2 | 5 | 426 ± 81 | 527 ± 153 | 664 ± 117 | 756 ± 143 |
| Left | 2 | 6 | 487 ± 106 | 527 ± 192 | 679 ± 138 | 858 ± 189 |
| Left | 4 | None | 267 ± 42 | 303 ± 58 | 426 ± 69 | 534 ± 73 |
| Left | 4 | 3 | 383 ± 48 | 441 ± 63 | 611 ± 67 | 678 ± 77 |
| Left | 4 | 4 | 421 ± 61 | 499 ± 65 | 636 ± 84 | 737 ± 104 |
| Left | 4 | 5 | 468 ± 119 | 497 ± 152 | 742 ± 185 | 795 ± 163 |
| Left | 4 | 6 | 504 ± 148 | 538 ± 163 | 753 ± 168 | 849 ± 225 |
| Right | 1 | None | 211 ± 55 | 251 ± 48 | 353 ± 57 | 453 ± 53 |
| Right | 1 | 3 | 265 ± 63 | 299 ± 63 | 408 ± 106 | 479 ± 99 |
| Right | 1 | 4 | 336 ± 82 | 377 ± 130 | 531 ± 94 | 581 ± 128 |
| Right | 1 | 5 | 387 ± 110 | 430 ± 139 | 528 ± 143 | 604 ± 130 |
| Right | 1 | 6 | 455 ± 158 | 458 ± 151 | 629 ± 173 | 748 ± 166 |
| Right | 2 | None | 233 ± 55 | 271 ± 45 | 382 ± 58 | 467 ± 61 |
| Right | 2 | 3 | 315 ± 65 | 371 ± 67 | 480 ± 93 | 567 ± 58 |
| Right | 2 | 4 | 386 ± 74 | 453 ± 86 | 588 ± 102 | 636 ± 101 |
| Right | 2 | 5 | 434 ± 107 | 505 ± 141 | 658 ± 113 | 692 ± 164 |
| Right | 2 | 6 | 465 ± 144 | 470 ± 164 | 715 ± 164 | 737 ± 196 |
| Right | 4 | None | 243 ± 52 | 278 ± 32 | 386 ± 50 | 491 ± 79 |
| Right | 4 | 3 | 362 ± 52 | 408 ± 87 | 568 ± 79 | 658 ± 99 |
| Right | 4 | 4 | 415 ± 89 | 474 ± 80 | 623 ± 117 | 719 ± 149 |
| Right | 4 | 5 | 471 ± 133 | 463 ± 124 | 679 ± 123 | 753 ± 201 |
| Right | 4 | 6 | 454 ± 137 | 499 ± 176 | 747 ± 223 | 801 ± 199 |

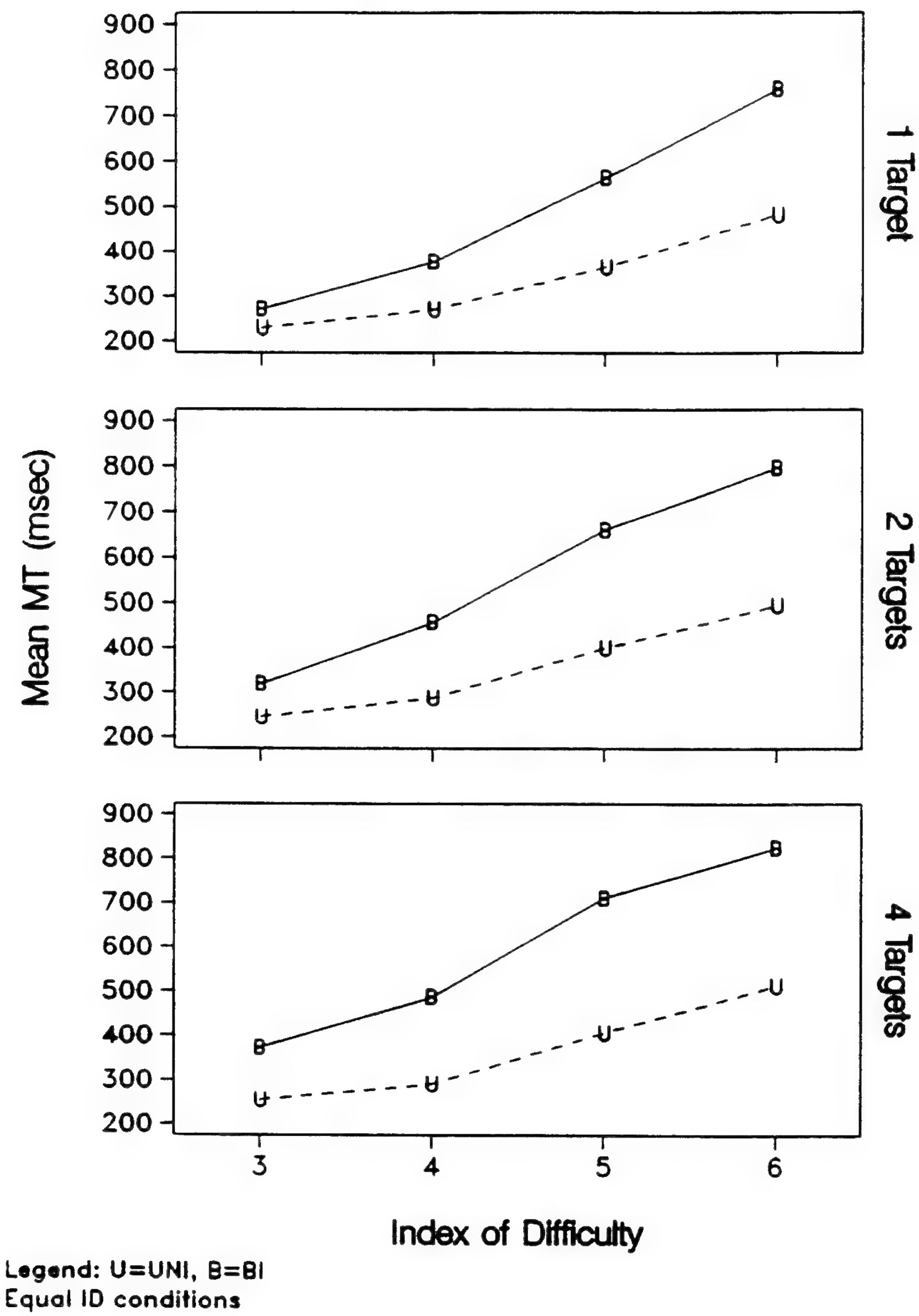



Figure 5.12. Unimanual and Bimanual Comparison of MT vs. ID.

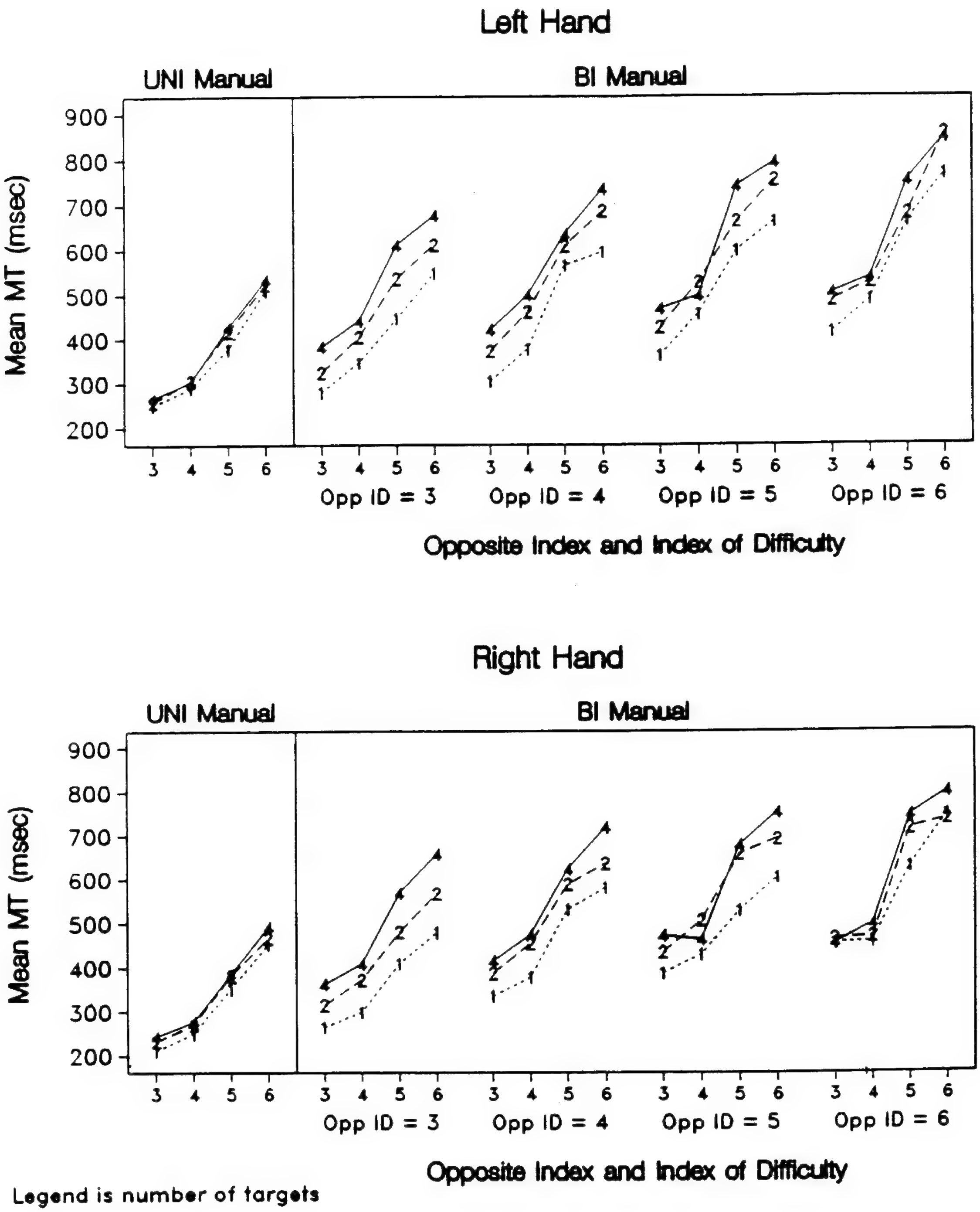



Figure 5.13. MT vs. ID by N, OPID and HAND.

alternatives increased. ID was significant, $F(3,54) = 611.99$, $p \leq 0.0001$, with MT increasing as ID increased. HAND was significant, $F(1,18) = 51.37$, $p \leq 0.0001$, with right hand movements faster than left (335 vs. 372 msec). The HAND x ID interaction was significant, $F(3,54) = 3.08$, $p = 0.0351$. The significance of ID was expected from Fitts' Law and is very strong under the conditions tested. However, the significance of the number of target alternatives was not expected.

Under similar conditions, Fowler et al. (1991) found manual condition, hand, and ID, to be significant main effects with respect to movement time. They reported no significant interactions. To compare results with the results of Fowler et al. (1991), a 2 x 2 x 4 x 3 repeated measures analysis of variance (COND x N x ID x HAND) was conducted on the combined unimanual and bimanual equal-ID movement time data. The following model was used:

$$Y_{ijkl} = \mu + COND_i + HAND_j + COND{\times}HAND_{ij} + ID_k + COND{\times}ID_{ik} +$$

$$HAND{\times}ID_{jk} + COND{\times}HAND{\times}ID_{ijk} + N_l + COND{\times}N_{il} + HAND{\times}N_{jl} + ID{\times}N_{kl} +$$

$$COND{\times}HAND{\times}N_{ijl} + COND{\times}ID{\times}N_{ikl} + HAND{\times}ID{\times}N_{jkl} + \epsilon_{ijkl}$$

where

$Y_{ijkl}$ = MT for the $i^{th}$ COND, the $j^{th}$ HAND, the $k^{th}$ ID, and the $l^{th}$ target set

$\mu$ = mean

$COND_i$ = manual condition (unimanual, bimanual)

$HAND_j$ = hand (left,right)

$ID_k$ = index of difficulty (3,4,5,6)

$N_l$ = number of target alternatives (1,2,4)

$\epsilon_{ijkl}$ = random error.

The ANOVA results are summarized in Table 5.18. COND (unimanual vs. bimanual) was significant, $F(1,18) = 207.9$, $p \leq 0.0001$, with unimanual reactions faster (353 vs. 550 msec). The number of target alternatives was significant, $F(2,36) = 34.06$, $p \leq 0.0001$, with MT increasing with increasing N. ID was significant, $F(3,54) = 368.82$, $p \leq 0.0001$, with higher IDs resulting in slower movements (283 vs. 362 vs. 518 vs. 645 msec). HAND was significant, $F(1,1) = 10.37$, $p = 0.0047$, with the right hand faster than left (434 vs. 469 msec). COND x ID was significant, $F(3,54) = 46.16$, $p \leq 0.0001$, and COND x N was significant, $F(2,36) = 11.42$, $p \leq 0.0001$.

Separate repeated measures ANOVAs were conducted on the MT data for each of the levels of N (Table 5.19). COND, HAND and ID and the COND x ID interactions were all significant for N = 1, N = 2 and N = 4. Appendix G presents the mean MT values for all conditions tested.

Table 5.18. MT ANOVA for Bimanual Equal-ID Task.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, EQUAL ID CONDITIONS

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 8801726 | 18 | 762037 | 207.90 | 0.0001 |
| HAND | 1 | 284946 | 18 | 494514 | 10.37 | 0.0047 |
| ID | 3 | 17883573 | 54 | 872801 | 368.82 | 0.0001 |
| TARGETS | 2 | 712046 | 36 | 376267 | 34.06 | 0.0001 |
| COND*HAND | 1 | 648 | 18 | 447464 | 0.03 | 0.8736 |
| COND*ID | 3 | 1664788 | 54 | 649235 | 46.16 | 0.0001 |
| HAND*ID | 3 | 49651 | 54 | 507562 | 1.76 | 0.1656 |
| COND*TARGETS | 2 | 228425 | 36 | 360081 | 11.42 | 0.0001 |
| HAND*TARGETS | 2 | 481 | 36 | 162345 | 0.05 | 0.9482 |
| ID*TARGETS | 6 | 54570 | 108 | 530816 | 1.85 | 0.0960 |
| COND*HAND*ID | 3 | 13300 | 54 | 443947 | 0.54 | 0.6574 |
| COND*HAND*TARGETS | 2 | 4089 | 36 | 158109 | 0.47 | 0.6316 |
| COND*ID*TARGETS | 6 | 29631 | 108 | 545351 | 0.98 | 0.4438 |
| HAND*ID*TARGETS | 6 | 39893 | 108 | 398096 | 1.80 | 0.1050 |
| COND*HAND*ID*TARGETS | 6 | 38735 | 108 | 391184 | 1.78 | 0.1094 |

Table 5.19. MT ANOVA by Target Alternative Levels.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, EQUAL ID CONDITIONS BY TARGET

INDEPENDENT VARIABLES

CONDITION: UNI, BI
HAND: LEFT, RIGHT
INDEX OF DIFF: 3, 4, 5, 6

TARGETS=1

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 1835989 | 18 | 203650 | 162.28 | 0.0001 |
| HAND | 1 | 84322 | 18 | 211408 | 7.18 | 0.0153 |
| ID | 3 | 6039948 | 54 | 377484 | 288.01 | 0.0001 |
| COND*HAND | 1 | 3908 | 18 | 154069 | 0.46 | 0.5078 |
| COND*ID | 3 | 603878 | 54 | 312284 | 34.81 | 0.0001 |
| HAND*ID | 3 | 8658 | 54 | 313004 | 0.50 | 0.6853 |
| COND*HAND*ID | 3 | 22044 | 54 | 276938 | 1.43 | 0.2433 |

TARGETS=2

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 3087282 | 18 | 295968 | 187.76 | 0.0001 |
| HAND | 1 | 101561 | 18 | 154215 | 11.85 | 0.0029 |
| ID | 3 | 5992521 | 54 | 529675 | 203.64 | 0.0001 |
| COND*HAND | 1 | 80 | 18 | 125716 | 0.01 | 0.9162 |
| COND*ID | 3 | 594040 | 54 | 439102 | 24.35 | 0.0001 |
| HAND*ID | 3 | 68142 | 54 | 251024 | 4.89 | 0.0045 |
| COND*HAND*ID | 3 | 28085 | 54 | 225046 | 2.25 | 0.0934 |

TARGETS=4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| COND | 1 | 4106880 | 18 | 622499 | 118.75 | 0.0001 |
| HAND | 1 | 99543 | 18 | 291236 | 6.15 | 0.0232 |
| ID | 3 | 5905675 | 54 | 496458 | 214.12 | 0.0001 |
| COND*HAND | 1 | 748 | 18 | 325789 | 0.04 | 0.8411 |
| COND*ID | 3 | 496501 | 54 | 443200 | 20.16 | 0.0001 |
| HAND*ID | 3 | 12744 | 54 | 341630 | 0.67 | 0.5733 |
| COND*HAND*ID | 3 | 1906 | 54 | 333147 | 0.10 | 0.9580 |

Figure 5.12 presents MT as a function of ID by the number of target alternatives for the bimanual equal-ID conditions. Notice the COND x ID interaction. As ID increased, for each target alternative set, the difference between unimanual and bimanual MT performance increased. Notice too, that as the number of target alternatives increased from one to two to four, the unimanual/bimanual difference increased which clearly demonstrated the COND x N interaction.

Figure 5.13 presents MT as a function of ID by hand and by OPID. Notice how tightly packed the unimanual MT results were across the target alternative sets. The N = 1, 2, and 4 conditions behaved similarly with only a slight upward shift as N increased. Notice the bend at ID = 4. This is a sign that Fitts' Law may under-predict MT at ID extremes (Wickens, 1992). The bend at ID = 4 may have also resulted from the fact that the easy ID = 3 task mostly involves wrist motion, chiefly characterized by rotation of the radius about the ulna and with abduction and extension of the wrist. The higher ID tasks (ID > 4) require more full arm motion characterized by extension of the whole arm-hand-wrist linkage (see Langolf, Chaffin, and Foulke, 1976). Left hand and right hand behavior seemed to not be different except for an upward shift for the left hand meaning longer movement times. The bend at ID = 4 may also be the result of additional visual scanning requirements of the longer movement amplitude associated with ID = 5 and 6. It is only at 16 inches that those IDs occur.

Clearly, when the contralateral limb was added, an upward shift in MT resulted. As OPID increased for both the left and right hands, an upward shift in MT occurred.

### 5.3.5 MT - Bimanual Equal-ID vs. Unequal-ID

Table 5.18 and Appendix H present the mean MT data for all conditions tested. Separate 2 x 3 x 4 repeated measures ANOVAs (N x OPID x HAND) were conducted on MT data at each ID (3, 4, 5 and 6) treating subjects as a random factor (Table 5.20). The bimanual equal-ID versus the bimanual unequal-ID conditions were compared. At each ID level, the number of target alternatives was significant ($p \leq 0.0001$) and OPID was significant ($p \leq 0.0001$). No significant interactions were found.

Contrasts showed (Table 5.21) that OPID = 3 was always in a class by itself and was significantly different for all levels of ID. However, at ID = 3, OPIDs 5 and 6 were paired and 4 was significantly different than the others. At ID = 4, OPIDs 4 and 5 and OPIDs 5 and 6 were the same. At ID = 5, OPIDs 4 and 5 and OPIDs 5 and 6 were again the same. At ID = 6, all OPIDs were significantly different.

Figures 5.14 through Figure 5.18 present left hand and right hand MT regressed on ID averaged over all subjects. These figures represent the individual target alternative conditions (N = 1, 2 and 4) as shown on the right side of the graph and the opposite ID conditions of 3, 4, 5 and 6 as noted at the bottom. Notice that the coefficient of determination ($R^2$) is given for each of the 30 resultant conditions and that only two were below 0.9. Both of the two that were below 0.9 involved the right hand, one at N = 4 and OPID = 5 and the other at N = 2 and OPID = 6. Most $R^2$ values were very close to 1.0. This suggests that the model used (Fitts' Law) accounted for a large amount of the variation in MT for the left and right hands under both the unimanual and bimanual conditions. Figure 5.19 presents MT as a function of ID by target alternatives

Table 5.20. MT ANOVA Bimanual Equal-ID vs. Unequal-ID by ID.

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

INDEPENDENT VARIABLES

HAND: LEFT, RIGHT
OPPOSITE INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

INDEX OF DIFFICULTY=3

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 1 | 18 | 375703 | 0.00 | 0.9946 |
| OPPOSITE | 3 | 1313626 | 54 | 787295 | 30.03 | 0.0001 |
| TARGETS | 2 | 550183 | 36 | 363267 | 27.26 | 0.0001 |
| HAND*OPPOSITE | 3 | 18283 | 54 | 294612 | 1.12 | 0.3503 |
| HAND*TARGETS | 2 | 28779 | 36 | 166741 | 3.11 | 0.0569 |
| OPPOSITE*TARGETS | 6 | 47648 | 108 | 439136 | 1.95 | 0.0787 |
| HAND*OPPOSIT*TARGETS | 6 | 20975 | 108 | 318728 | 1.18 | 0.3200 |

INDEX OF DIFFICULTY=4

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 99179 | 18 | 471925 | 3.78 | 0.0676 |
| OPPOSITE | 3 | 940151 | 54 | 1193488 | 14.18 | 0.0001 |
| TARGETS | 2 | 471219 | 36 | 382889 | 22.15 | 0.0001 |
| HAND*OPPOSITE | 3 | 16444 | 54 | 333683 | 0.89 | 0.4537 |
| HAND*TARGETS | 2 | 826 | 36 | 265041 | 0.06 | 0.9455 |
| OPPOSITE*TARGETS | 6 | 117798 | 108 | 1233983 | 1.72 | 0.1235 |
| HAND*OPPOSIT*TARGETS | 6 | 7902 | 108 | 577396 | 0.25 | 0.9598 |

Table 5.20. MT ANOVA Bimanual Equal-ID vs. Unequal-ID by ID (cont.).

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

INDEPENDENT VARIABLES

HAND: LEFT, RIGHT
OPPOSITE INDEX OF DIFF: 3, 4, 5, 6
TARGETS: 1, 2, 4

INDEX OF DIFFICULTY=5

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 95078 | 18 | 704034 | 2.43 | 0.1364 |
| OPPOSITE | 3 | 2233207 | 54 | 1355910 | 29.65 | 0.0001 |
| TARGETS | 2 | 1169575 | 36 | 731794 | 28.77 | 0.0001 |
| HAND*OPPOSITE | 3 | 39203 | 54 | 644263 | 1.10 | 0.3591 |
| HAND*TARGETS | 2 | 20392 | 36 | 369039 | 0.99 | 0.3798 |
| OPPOSITE*TARGETS | 6 | 91010 | 108 | 882661 | 1.86 | 0.0950 |
| HAND*OPPOSIT*TARGETS | 6 | 30450 | 108 | 825581 | 0.66 | 0.6789 |

INDEX OF DIFFICULTY=6

| SOURCE | DF | SSQ | ERROR DF | ERROR SSQ | F-VALUE | P-VALUE |
|---|---|---|---|---|---|---|
| HAND | 1 | 257284 | 18 | 1263282 | 3.67 | 0.0716 |
| OPPOSITE | 3 | 2508789 | 54 | 866402 | 52.12 | 0.0001 |
| TARGETS | 2 | 1196863 | 36 | 625562 | 34.44 | 0.0001 |
| HAND*OPPOSITE | 3 | 19695 | 54 | 1079060 | 0.33 | 0.8047 |
| HAND*TARGETS | 2 | 29795 | 36 | 381473 | 1.41 | 0.2583 |
| OPPOSITE*TARGETS | 6 | 94624 | 108 | 796710 | 2.14 | 0.0548 |
| HAND*OPPOSIT*TARGETS | 6 | 43138 | 108 | 1296572 | 0.60 | 0.7307 |

Table 5.21. Bimanual MT Contrasts (OPID).

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, BIMANUAL EQUAL ID VS UNEQUAL ID

PAIRWISE COMPARISON OF OPPOSITE INDEX OF DIFFICULTY FOR EACH INDEX OF DIFFICULTY

| ID | MSD(TUKEY) | OPPID LEVEL 1 | OPPID LEVEL 2 | MEAN LEVEL 1 | MEAN LEVEL 2 | MEAN DIFF | SIGNIFICANTLY DIFFERENT |
|---|---|---|---|---|---|---|---|
| 3 | 42.4 | 3 | 4 | 321.2 | 372.3 | 51.1 | * |
| 3 | 42.4 | 3 | 5 | 321.2 | 424.9 | 103.7 | * |
| 3 | 42.4 | 3 | 6 | 321.2 | 463.3 | 142.1 | * |
| 3 | 42.4 | 4 | 5 | 372.3 | 424.9 | 52.6 | * |
| 3 | 42.4 | 4 | 6 | 372.3 | 463.3 | 91.0 | * |
| 3 | 42.4 | 5 | 6 | 424.9 | 463.3 | 38.4 | |
| 4 | 52.2 | 3 | 4 | 378.5 | 440.3 | 61.8 | * |
| 4 | 52.2 | 3 | 5 | 378.5 | 479.9 | 101.4 | * |
| 4 | 52.2 | 3 | 6 | 378.5 | 496.4 | 117.9 | * |
| 4 | 52.2 | 4 | 5 | 440.3 | 479.9 | 39.6 | |
| 4 | 52.2 | 4 | 6 | 440.3 | 496.4 | 56.1 | * |
| 4 | 52.2 | 5 | 6 | 479.9 | 496.4 | 16.5 | |
| 5 | 55.6 | 3 | 4 | 508.2 | 592.0 | 83.8 | * |
| 5 | 55.6 | 3 | 5 | 508.2 | 644.8 | 136.7 | * |
| 5 | 55.6 | 3 | 6 | 508.2 | 697.7 | 189.5 | * |
| 5 | 55.6 | 4 | 5 | 592.0 | 644.8 | 52.9 | |
| 5 | 55.6 | 4 | 6 | 592.0 | 697.7 | 105.7 | * |
| 5 | 55.6 | 5 | 6 | 644.8 | 697.7 | 52.8 | |
| 6 | 44.5 | 3 | 4 | 590.4 | 659.1 | 68.7 | * |
| 6 | 44.5 | 3 | 5 | 590.4 | 710.6 | 120.2 | * |
| 6 | 44.5 | 3 | 6 | 590.4 | 793.5 | 203.1 | * |
| 6 | 44.5 | 4 | 5 | 659.1 | 710.6 | 51.5 | * |
| 6 | 44.5 | 4 | 6 | 659.1 | 793.5 | 134.4 | * |
| 6 | 44.5 | 5 | 6 | 710.6 | 793.5 | 82.9 | * |

Table 5.21. Bimanual MT Contrasts (Targets).

MAIN - ANALYSIS OF VARIANCE RESULTS FOR MOVEMENT TIME, BIMANUAL EQUAL ID VS. UNEQUAL ID

PAIRWISE COMPARISON OF TARGETS FOR EACH INDEX OF DIFFICULTY

| ID | MSD(TUKEY) | TARGETS LEVEL 1 | TARGETS LEVEL 2 | MEAN LEVEL 1 | MEAN LEVEL 2 | MEAN DIFF | SIGNIFICANTLY DIFFERENT |
|---|---|---|---|---|---|---|---|
| 3 | 28.2 | 1 | 2 | 350.3 | 401.1 | 50.7 | * |
| 3 | 28.2 | 1 | 4 | 350.3 | 434.8 | 84.5 | * |
| 3 | 28.2 | 2 | 4 | 401.1 | 434.8 | 33.8 | * |
| 4 | 28.9 | 1 | 2 | 403.9 | 464.9 | 61.0 | * |
| 4 | 28.9 | 1 | 4 | 403.9 | 477.5 | 73.6 | * |
| 4 | 28.9 | 2 | 4 | 464.9 | 477.5 | 12.7 | |
| 5 | 40.0 | 1 | 2 | 546.1 | 616.1 | 70.0 | * |
| 5 | 40.0 | 1 | 4 | 546.1 | 669.8 | 123.7 | * |
| 5 | 40.0 | 2 | 4 | 616.1 | 669.8 | 53.6 | * |
| 6 | 37.0 | 1 | 2 | 623.4 | 693.0 | 69.6 | * |
| 6 | 37.0 | 1 | 4 | 623.4 | 748.7 | 125.2 | * |
| 6 | 37.0 | 2 | 4 | 693.0 | 748.7 | 55.6 | * |

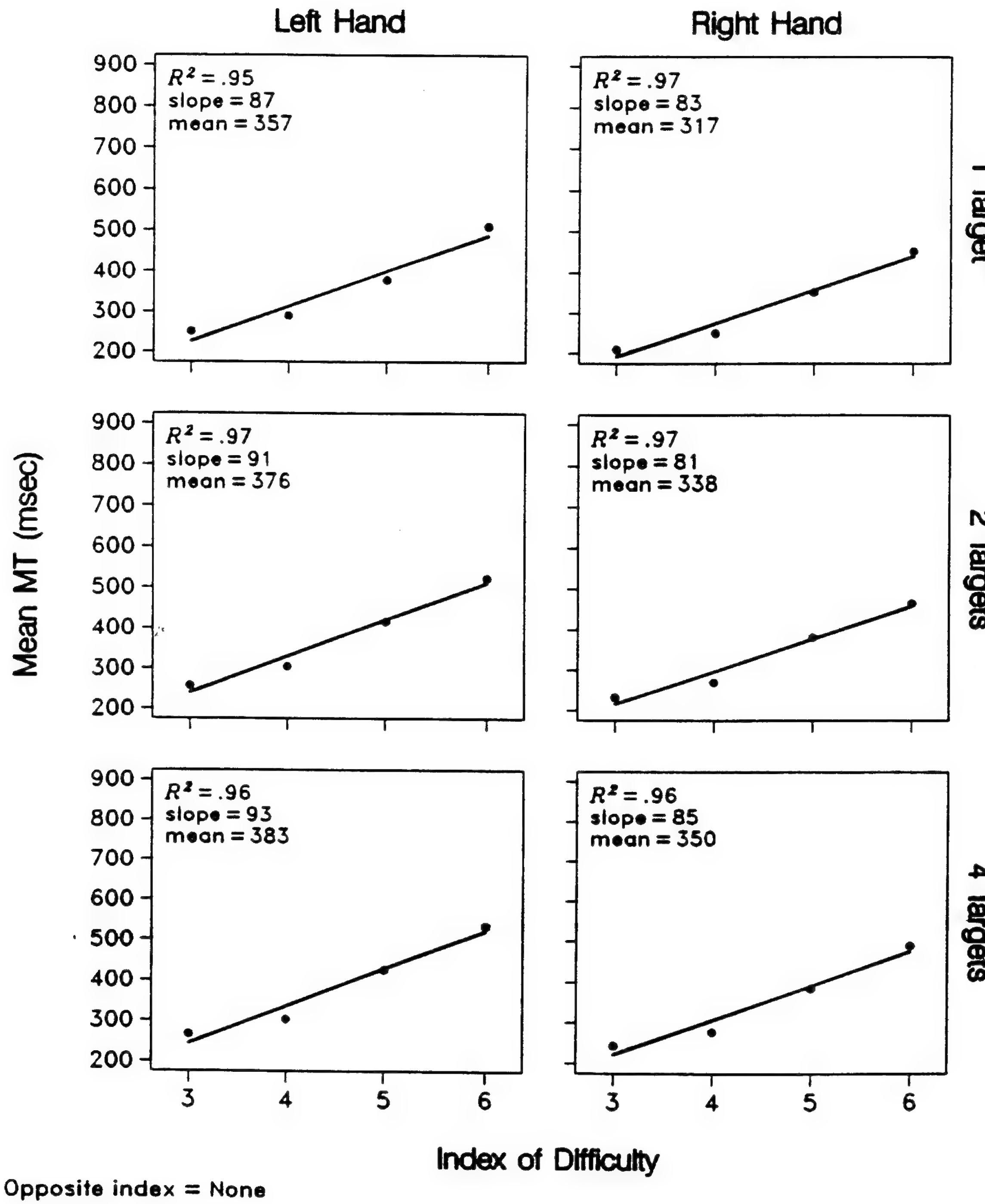



Figure 5.14. MT Regressed on ID (OPID = None).

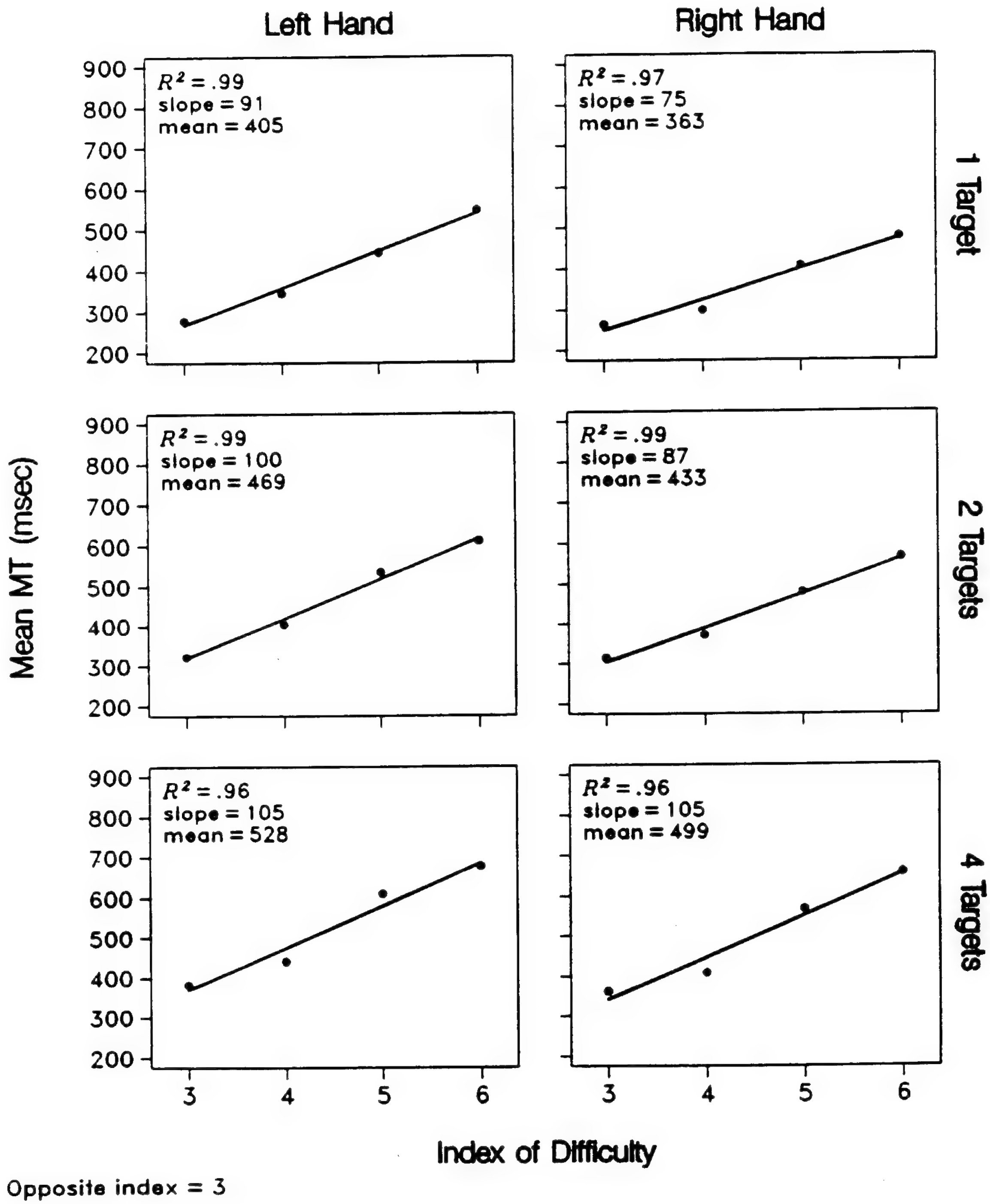



Figure 5.15. MT Regressed on ID (OPID = 3).

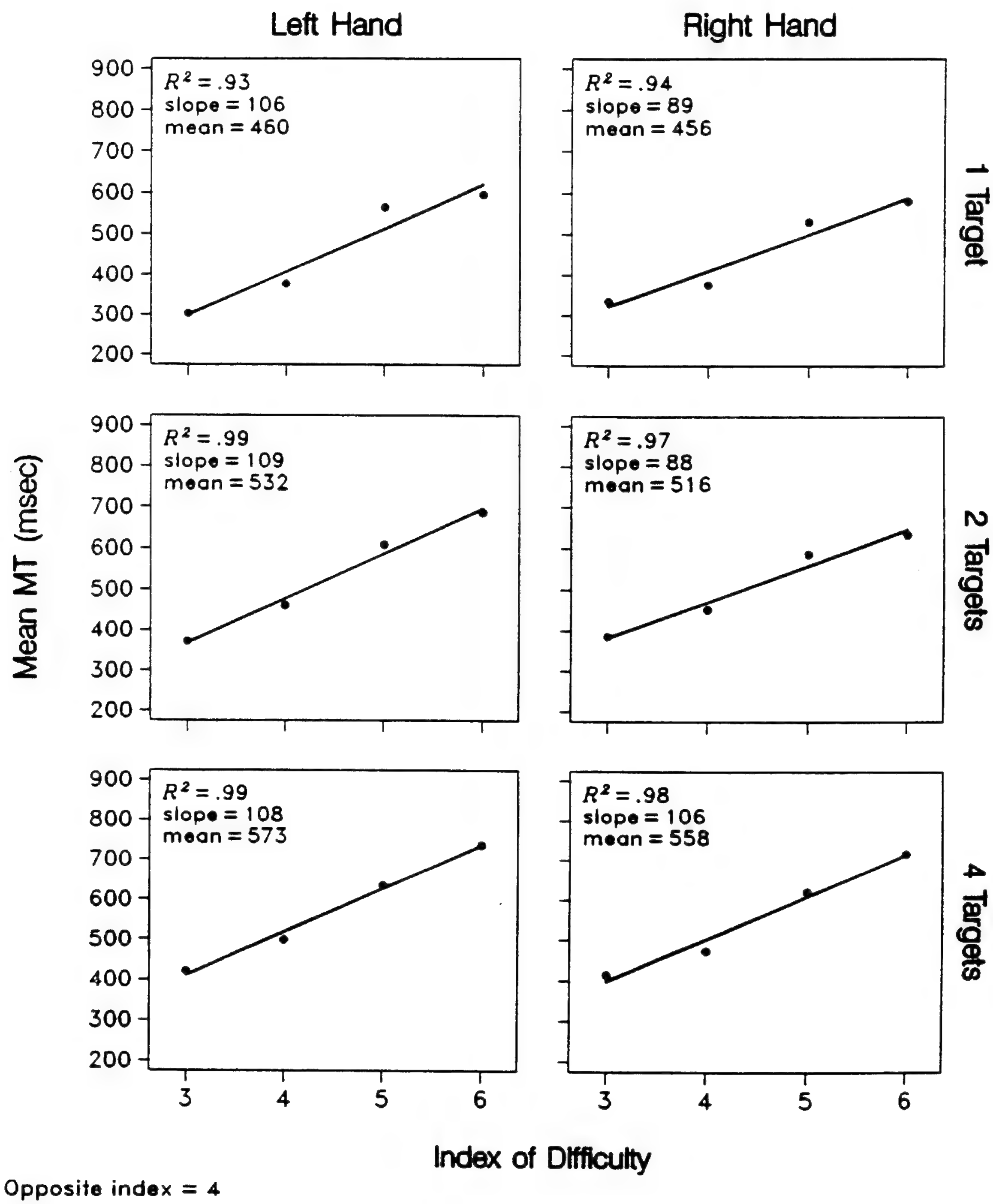



Figure 5.16. MT Regressed on ID (OPID = 4).

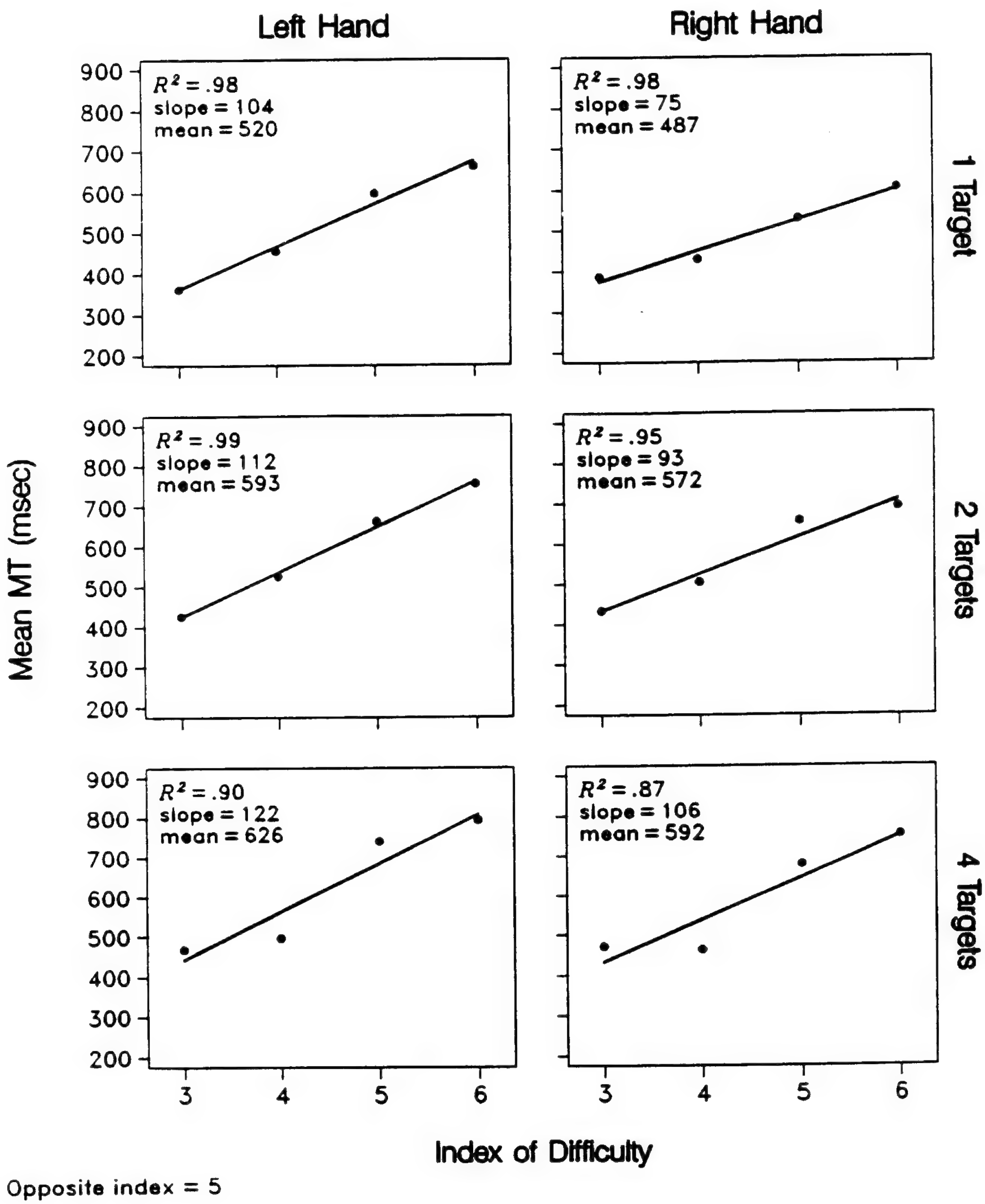



Figure 5.17. MT Regressed on ID (OPID = 5).

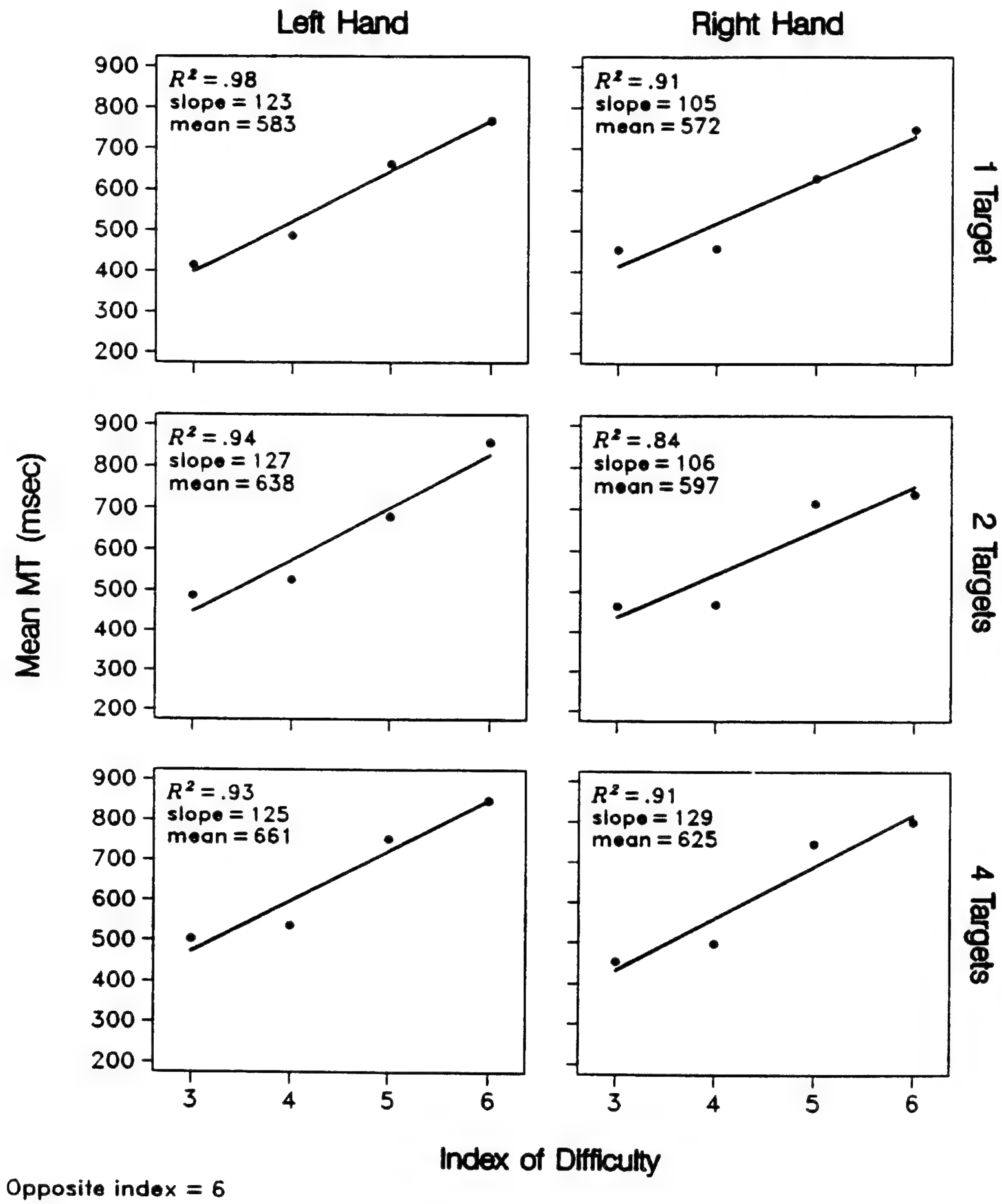



Figure 5.18. MT Regressed on ID (OPID = 6).

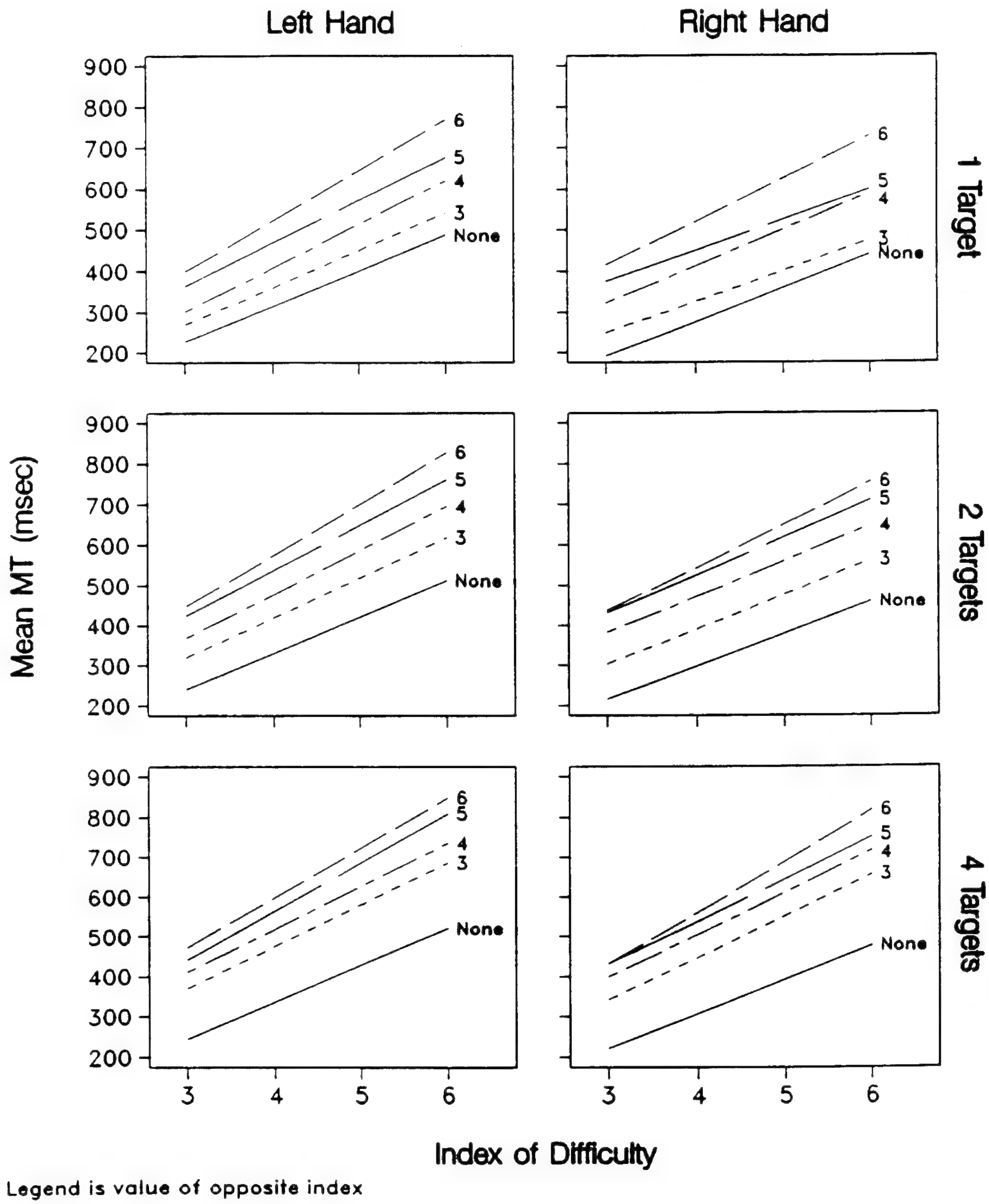



Figure 5.19. MT Regressed on ID - Comparing OPID by Hand.

for each OPID. Notice the upward shift in MT as the opposite task ID increases from NONE to 6. Table 5.18 presents the mean MT data for all bimanual unequal-ID conditions. These data suggest that all task movement times increased as OPID increased, and conversely, as OPID decreased, movement times decreased. Figure 5.20 presents mean MT as a function of OPID by ID and N. Notice the upward shift in MT with increasing OPID for *all* ID. Notice the OPID x N interaction and the upward shift with increasing N and ID. Figure 5.21 collapses ID and plots mean MT as a function of OPID by target alternatives.

### 5.3.6 Aiming Misses

First attempt misses were recorded manually by the experimenter. A total of 1,439 left and right misses were observed. The average number of misses by subjects was 76 with a standard deviation of 44.5. Table 5.22 tabulates the first-attempt misses by hand, number of targets, ID and opposite index of difficulty. Figure 5.22 presents the number of misses for the left and right hands as a function of the number of target alternatives, ID and OPID.

Interestingly, in most of the plots, the number of misses for the N = 1 condition exceeds the number of misses for the N = 4 condition. Perhaps, because the N = 1 condition required less decision making and less preprocessing before the movement began, carelessness resulted in less accurate movement execution. Alternatively, a speed-accuracy trade-off may have existed where faster movements resulting from fewer target

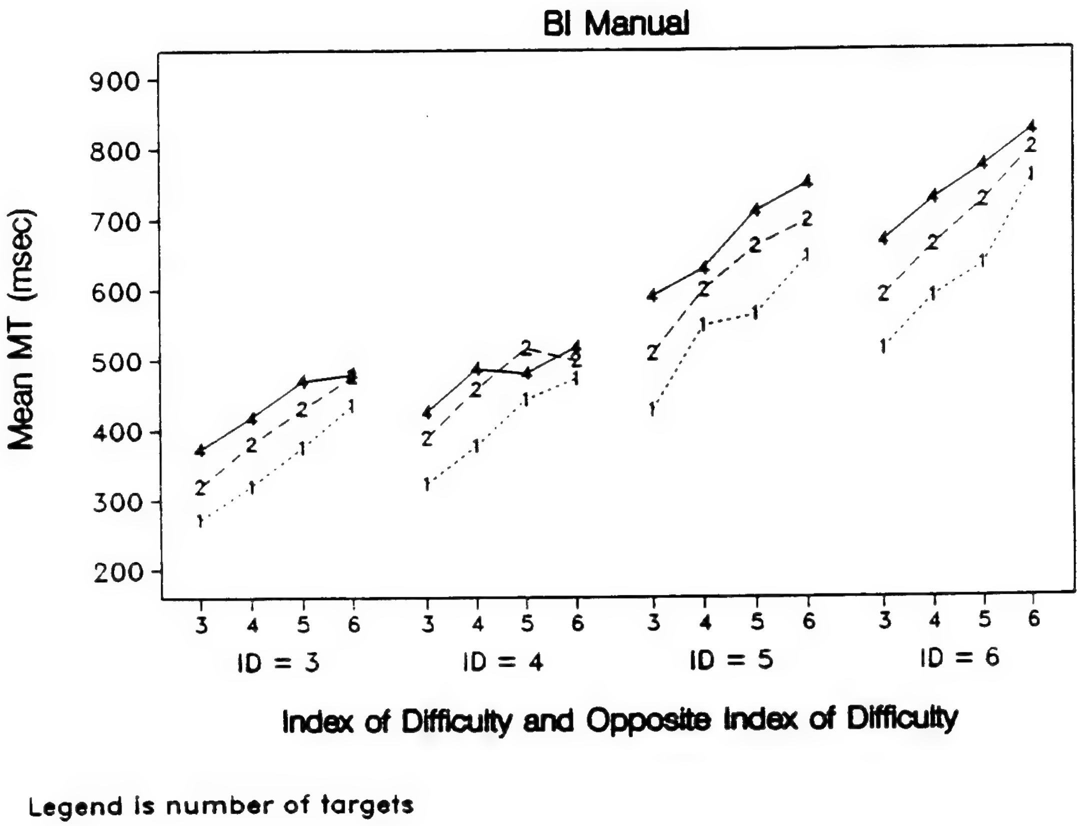



Figure 5.20. MT vs. OPID by ID and N.

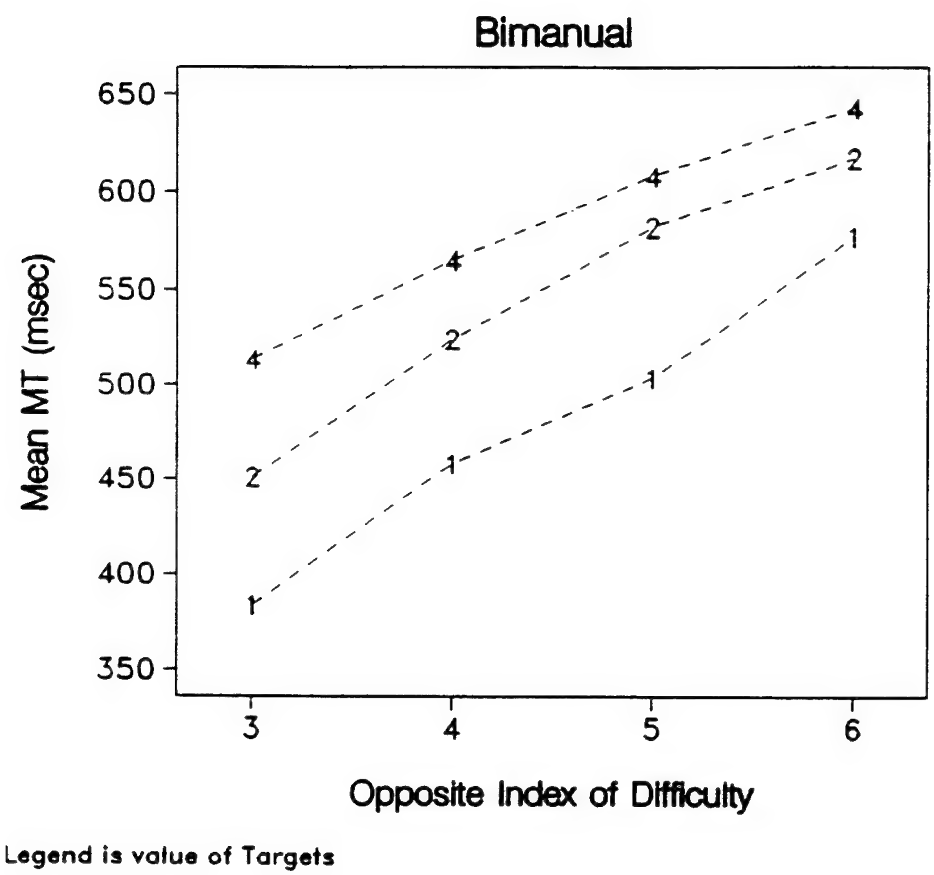



Figure 5.21. Mean MT vs. OPID by N.

Table 5.22. Misses by N, ID, OPID and HAND.

| Hand | Number of Targets | Opposite Index of Difficulty | First Attempt Misses ID = 3 | ID = 4 | ID = 5 | ID = 6 |
|---|---|---|---|---|---|---|
| Left | 1 | None | 5 | 9 | 18 | 20 |
| Left | 1 | 3 | 3 | 16 | 8 | 22 |
| Left | 1 | 4 | 5 | 21 | 12 | 23 |
| Left | 1 | 5 | 14 | 23 | 15 | 33 |
| Left | 1 | 6 | 4 | 22 | 26 | 22 |
| Left | 2 | None | 2 | 8 | 6 | 18 |
| Left | 2 | 3 | 3 | 10 | 13 | 19 |
| Left | 2 | 4 | 1 | 14 | 7 | 24 |
| Left | 2 | 5 | 3 | 8 | 14 | 16 |
| Left | 2 | 6 | 4 | 14 | 16 | 10 |
| Left | 4 | None | 6 | 8 | 12 | 23 |
| Left | 4 | 3 | 4 | 10 | 8 | 27 |
| Left | 4 | 4 | 3 | 12 | 14 | 24 |
| Left | 4 | 5 | 2 | 21 | 11 | 13 |
| Left | 4 | 6 | 3 | 10 | 7 | 30 |
| Right | 1 | None | 3 | 14 | 17 | 29 |
| Right | 1 | 3 | 7 | 5 | 8 | 33 |
| Right | 1 | 4 | 9 | 15 | 13 | 14 |
| Right | 1 | 5 | 6 | 13 | 15 | 10 |
| Right | 1 | 6 | 4 | 14 | 11 | 25 |
| Right | 2 | None | 5 | 9 | 12 | 15 |
| Right | 2 | 3 | 1 | 6 | 9 | 21 |
| Right | 2 | 4 | 8 | 11 | 6 | 28 |
| Right | 2 | 5 | 3 | 15 | 10 | 17 |
| Right | 2 | 6 | 2 | 4 | 9 | 7 |
| Right | 4 | None | 6 | 10 | 6 | 20 |
| Right | 4 | 3 | 2 | 10 | 10 | 18 |
| Right | 4 | 4 | 0 | 9 | 9 | 18 |
| Right | 4 | 5 | 4 | 9 | 8 | 16 |
| Right | 4 | 6 | 2 | 10 | 12 | 18 |

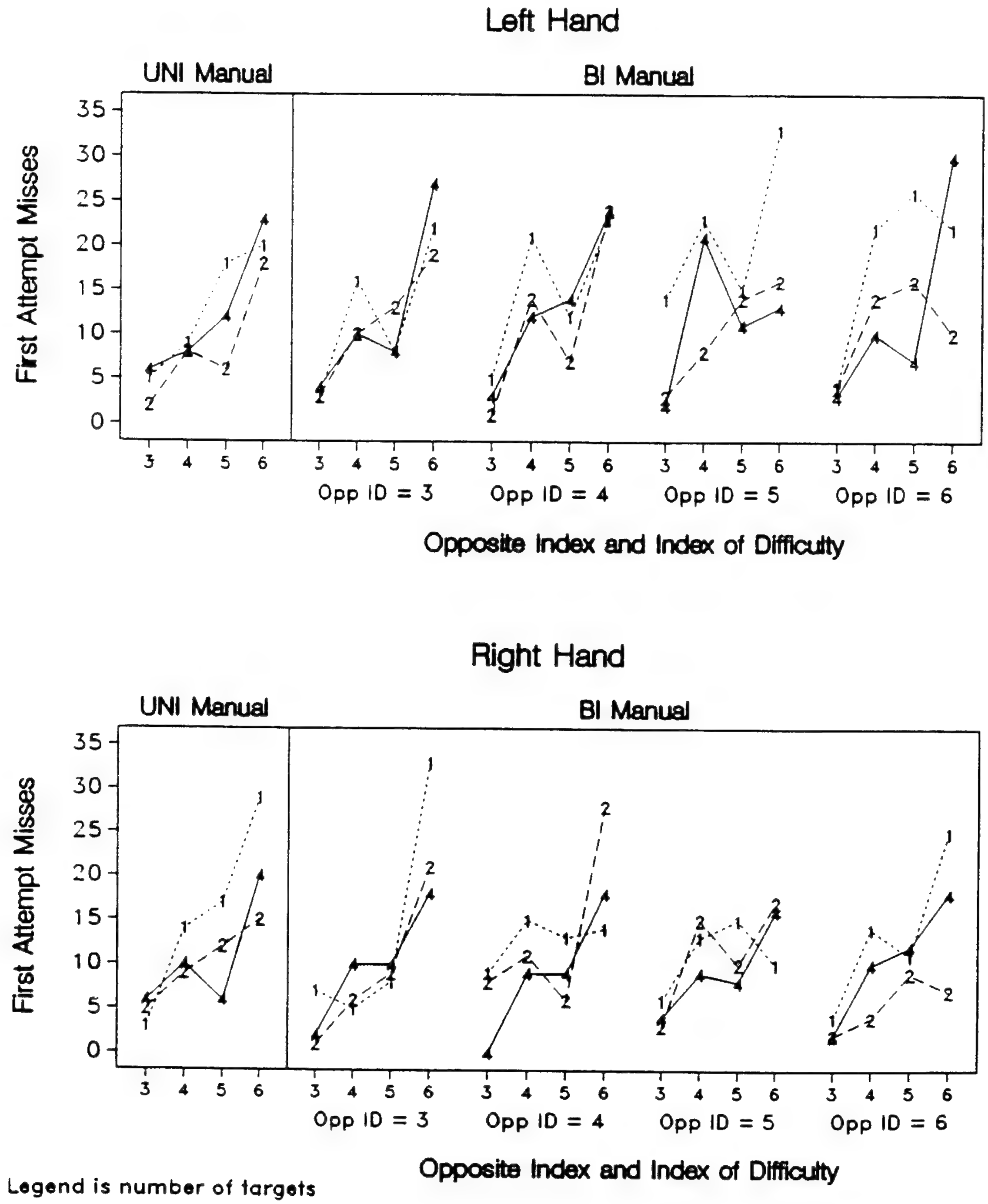



Figure 5.22. First-Attempt Misses vs. ID by HAND, N, and OPID.

alternatives were less accurate. From a purely observational standpoint, it seems that there was a tendency for increased misses from ID = 3 to ID = 4 for the bimanual condition across N, HAND and OPID. This increase was then followed by a decrease in misses from ID = 4 to ID = 5 and a further decrease from ID = 5 to ID = 6.

### 5.3.7 Errors

One hundred and ten unimanual and bimanual left-handed errors and one hundred and twelve right-handed errors were recorded by the controlling program. By definition, errors were only possible in the N = 2 and N = 4 conditions. Figure 5.23 presents the number of left-hand and right-hand errors as a function of ID and number of targets for the unimanual condition and plots left hand right hand errors as a function of ID, OPID, and number of targets for the bimanual condition. Under many of the bimanual conditions, the number of errors made a sharp increase at ID = 5. Errors then dropped off or rose slightly for the ID = 6 condition.

### 5.3.8 RT-MT Relationships

Mean unimanual and bimanual left hand and right hand reaction times were positively correlated across all IDs ($r = 0.85$). Figure 5.24 plots mean RT left versus mean RT right for the unimanual and bimanual equal-ID conditions by target alternative level. Slopes and $R^2$ values are shown. Notice how tightly packed the results are for the unimanual condition versus the bimanual condition.

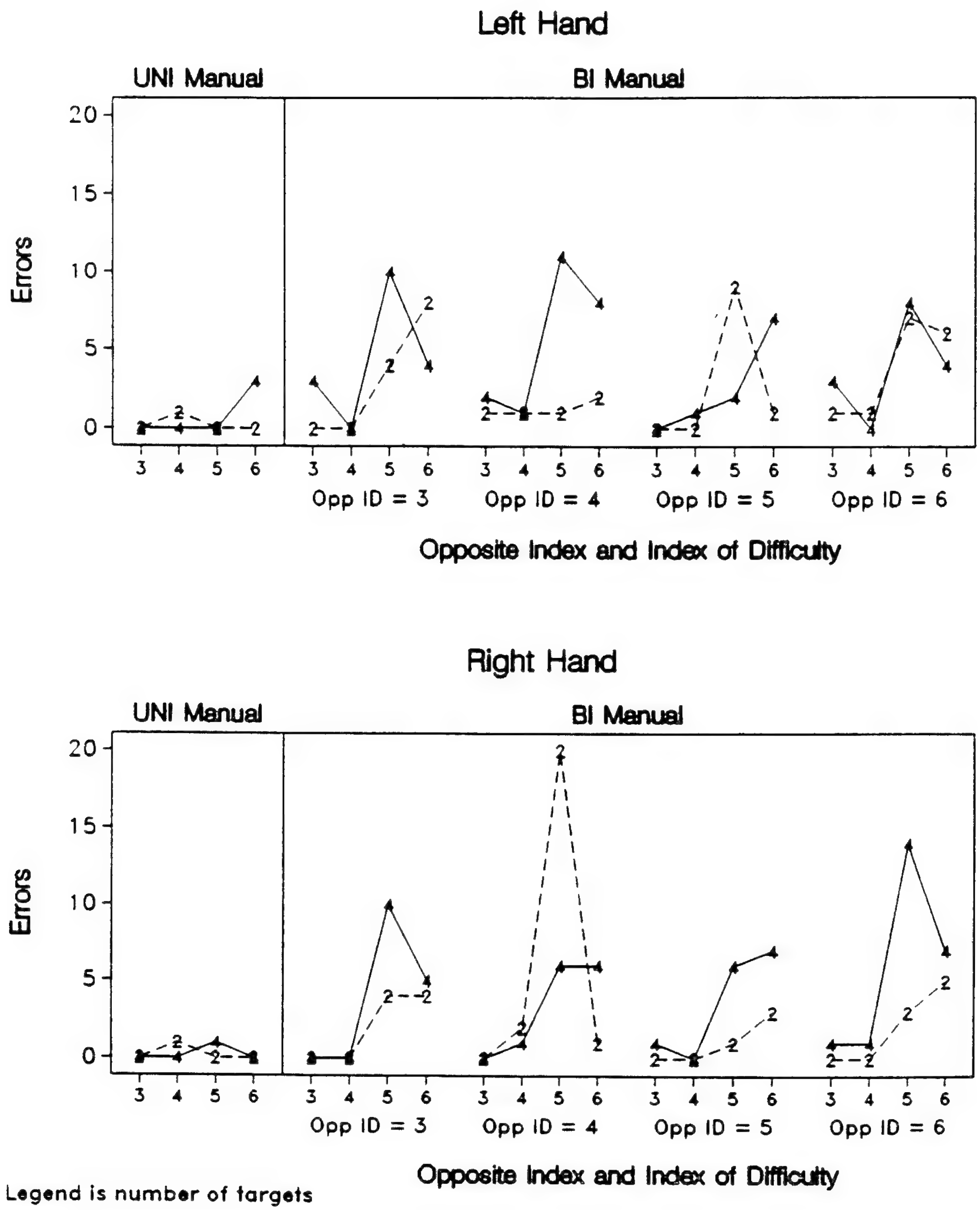



Figure 5.23. Errors vs. ID by HAND, N and OPID.

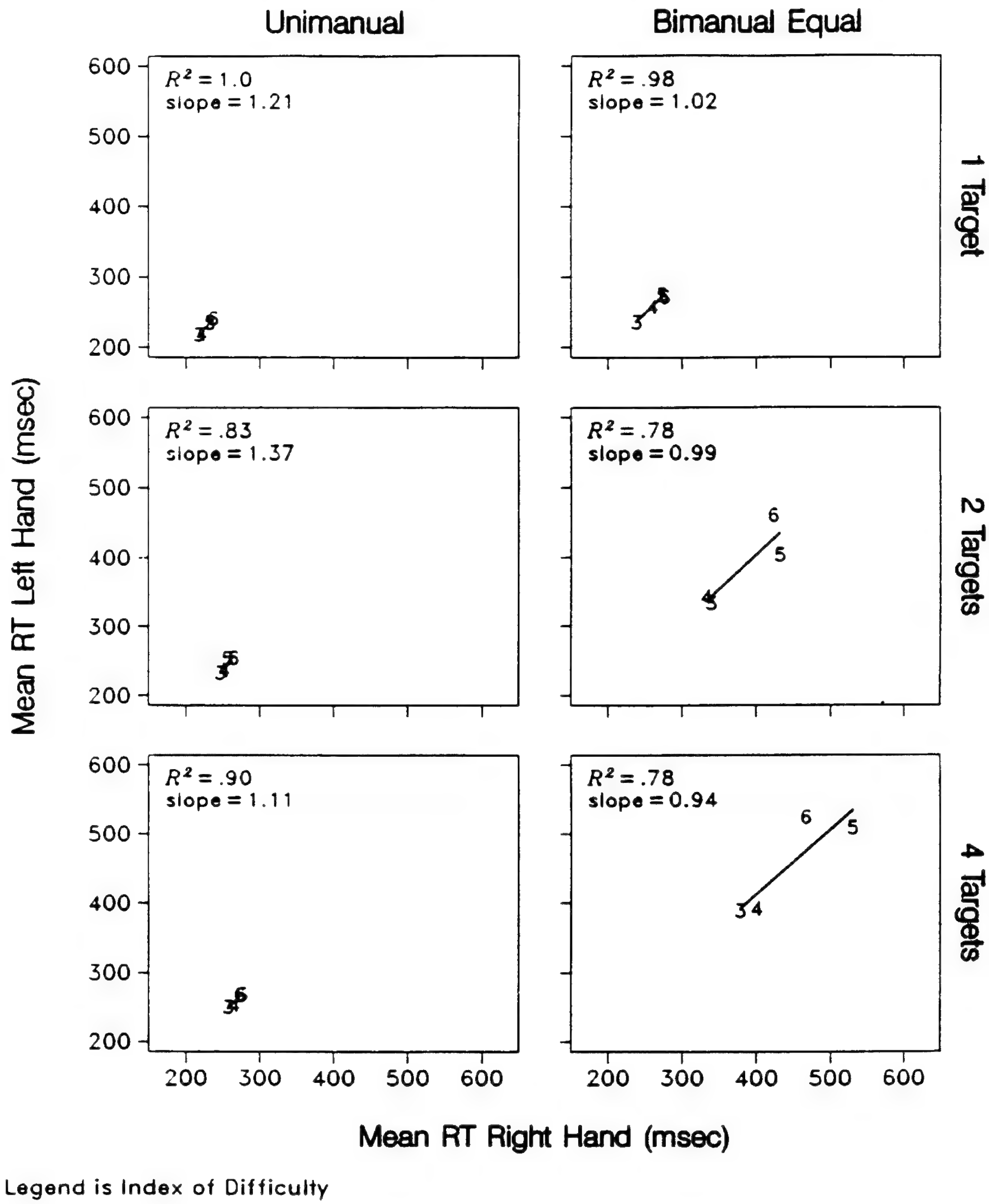



Figure 5.24. RTL vs. RTR.

Movement time left is plotted versus MT right in Figure 5.25 for the unimanual and bimanual conditions by target alternative level. Slopes and $R^2$ values are shown. Across all ID conditions, MT left was positively correlated with MT right ($r$ = 0.78).

Across all conditions, mean MT and mean RT were positively correlated ($r$ = 0.97). Figures 5.26 through 5.30 present MT vs. RT for increasing ID by hand, number of target alternatives, and by opposite index of difficulty. A feature common to most of these plots is that the ID = 3 and the ID = 4 RT vs. MT points are very close and seem to represent similar RT/MT response. Whereas the ID = 5 and the ID = 6 points are very closely spaced and seem to represent another similar RT/MT response. Slower RTs are associated with slower MTs, and faster RTs are associated with faster MTs.

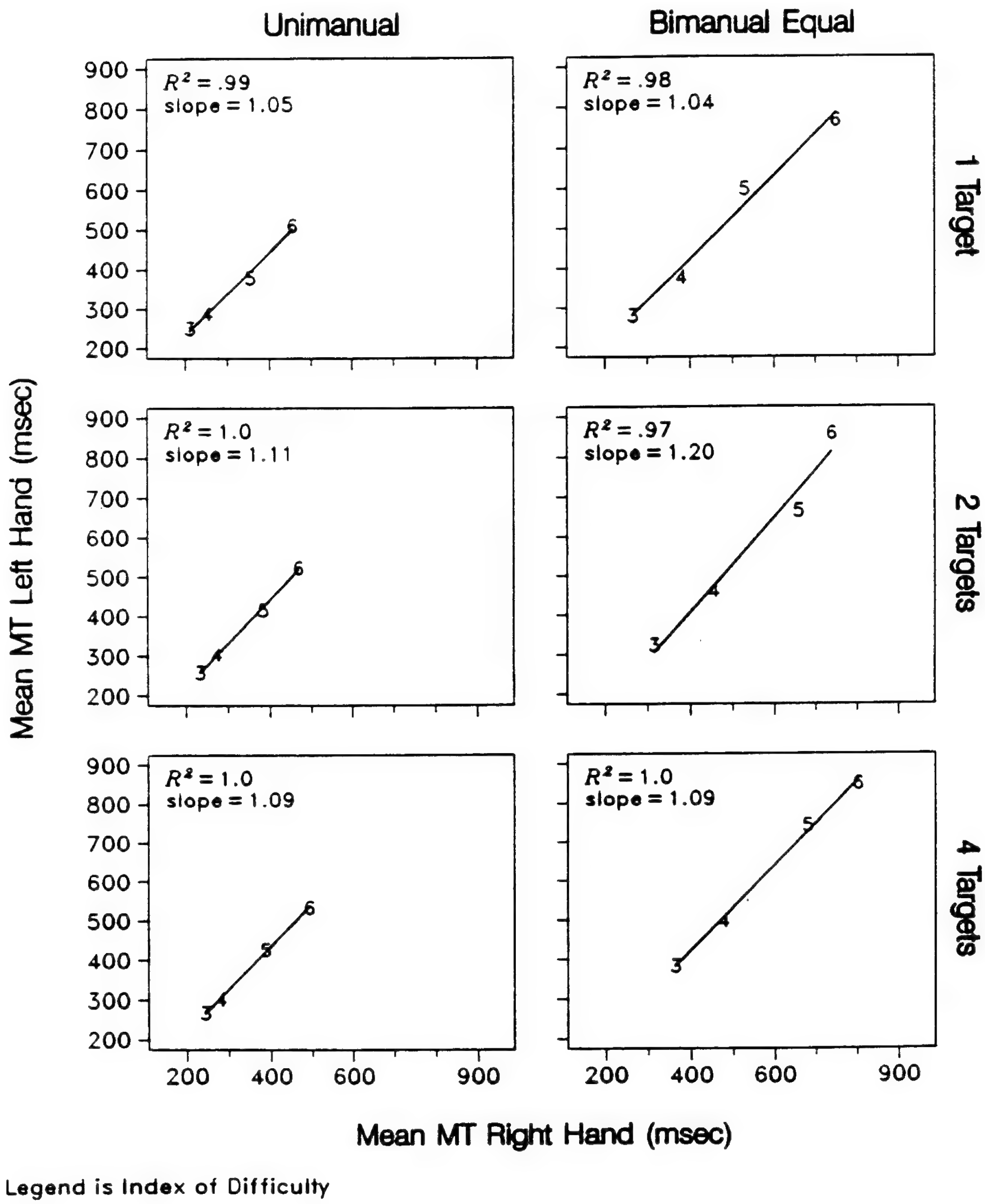
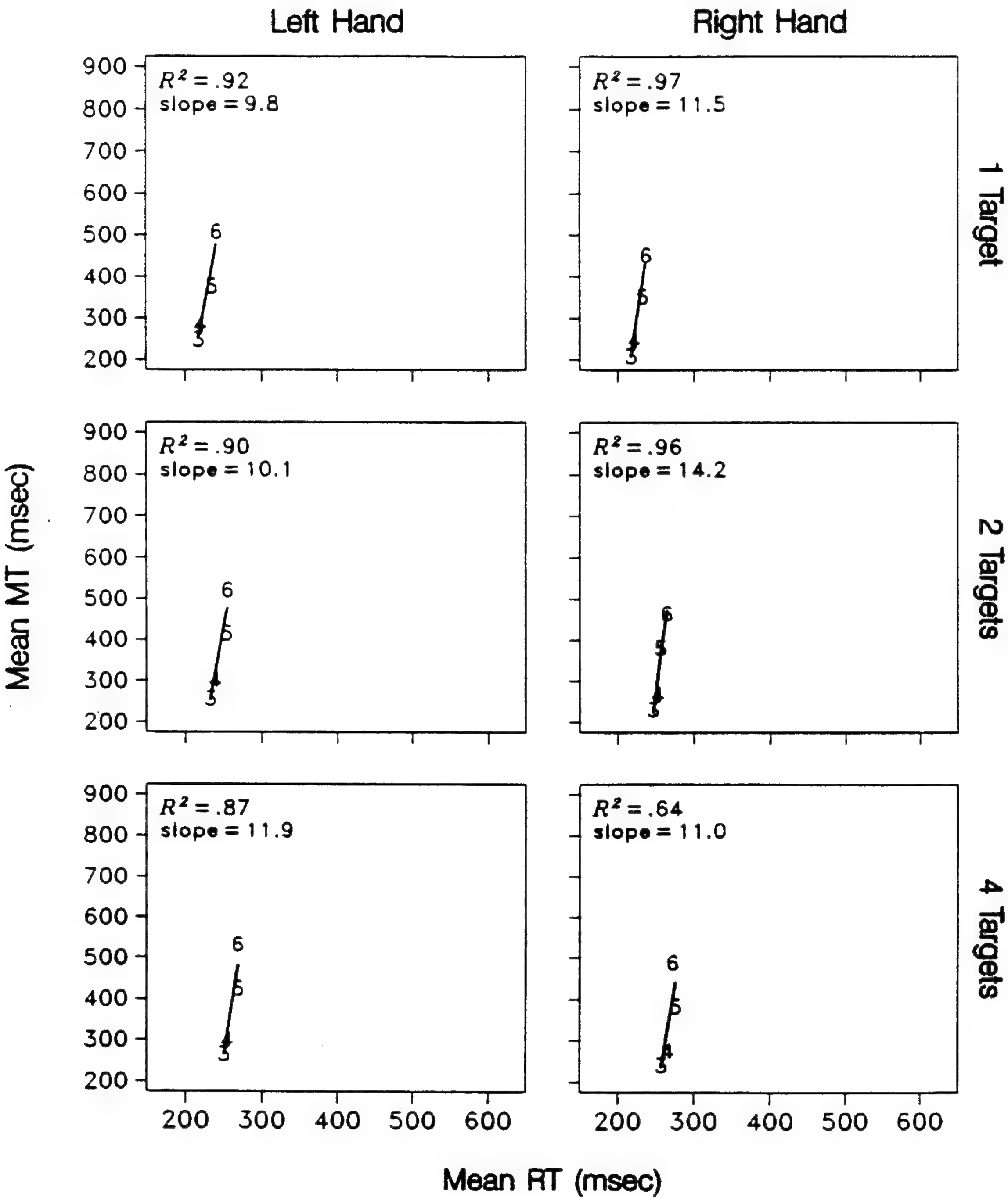



Figure 5.25. MTL vs. MTR.




Opposite index = None
Legend is index of difficulty

Figure 5.26. MT vs. RT (OPID = None).

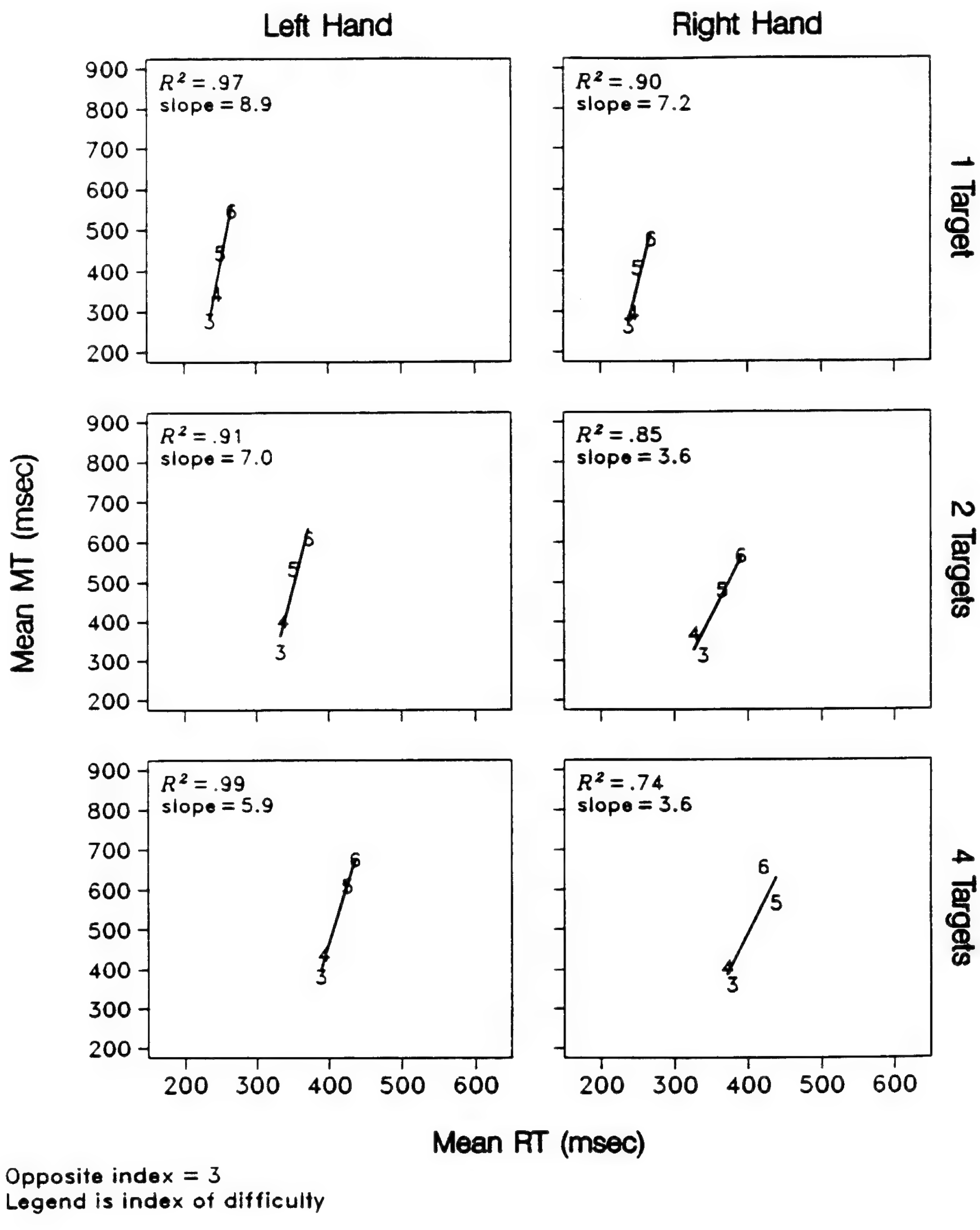



Figure 5.27. MT vs. RT (OPID = 3).

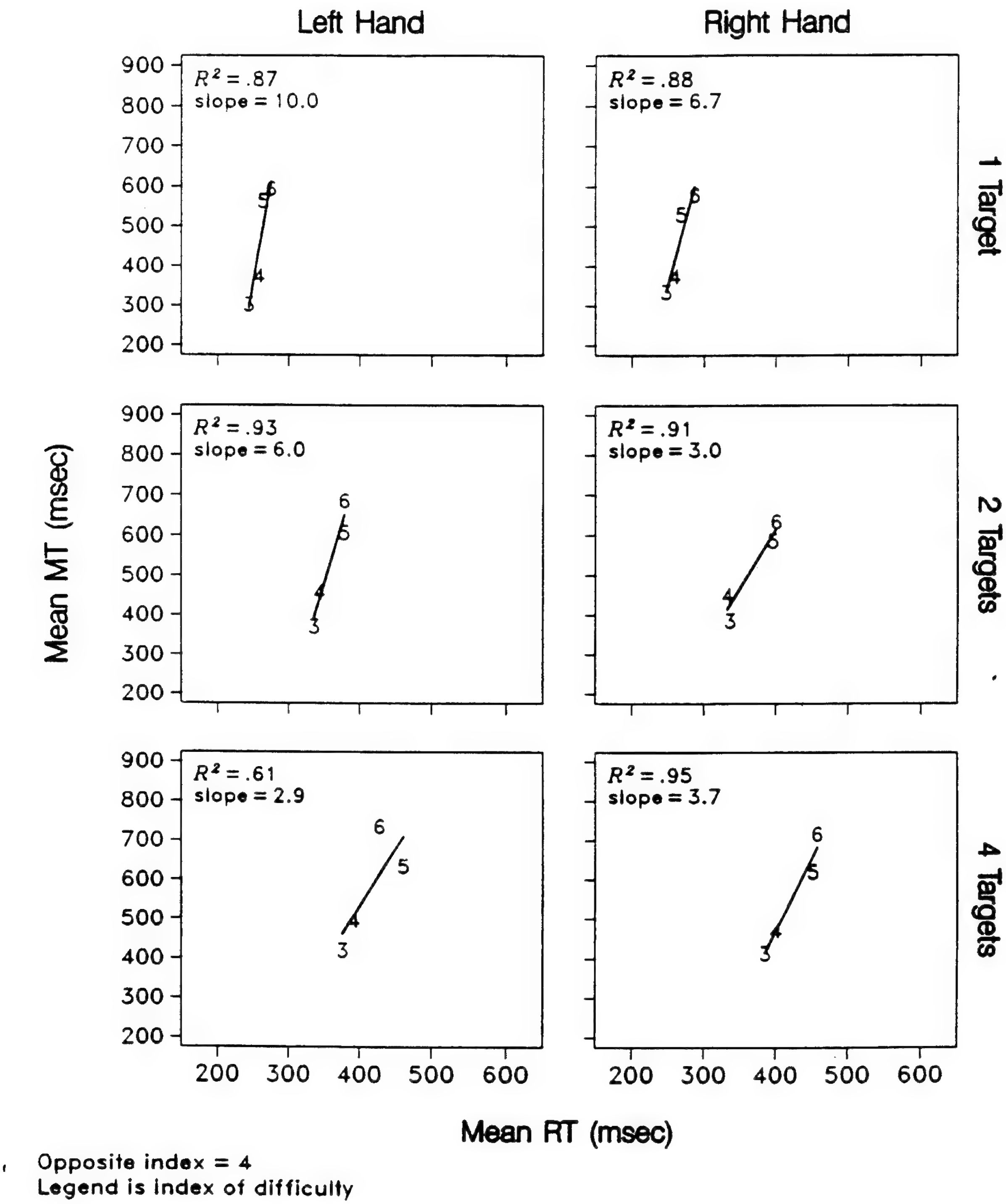



Figure 5.28. MT vs. RT (OPID = 4).

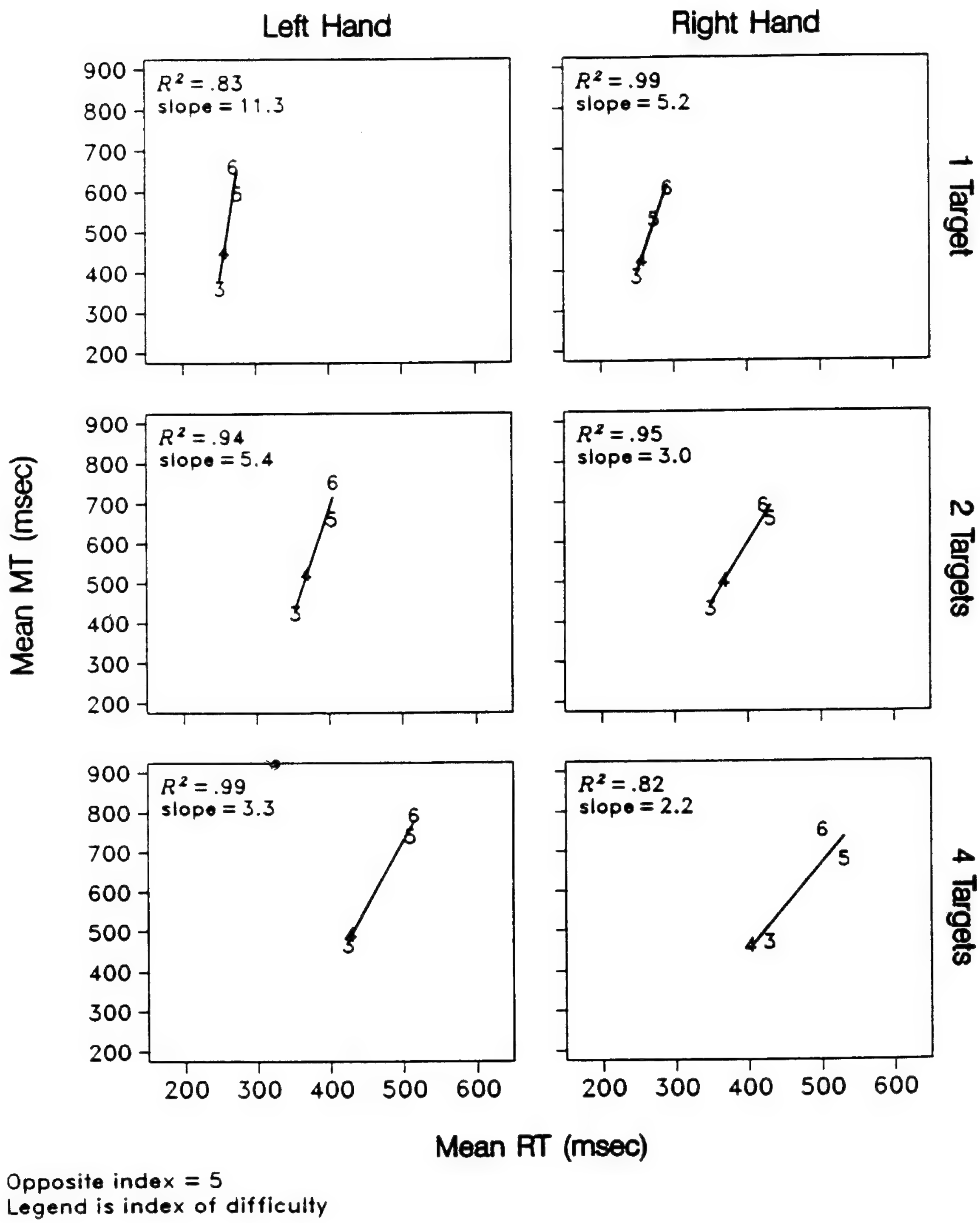



Figure 5.29. MT vs. RT (OPID = 5).

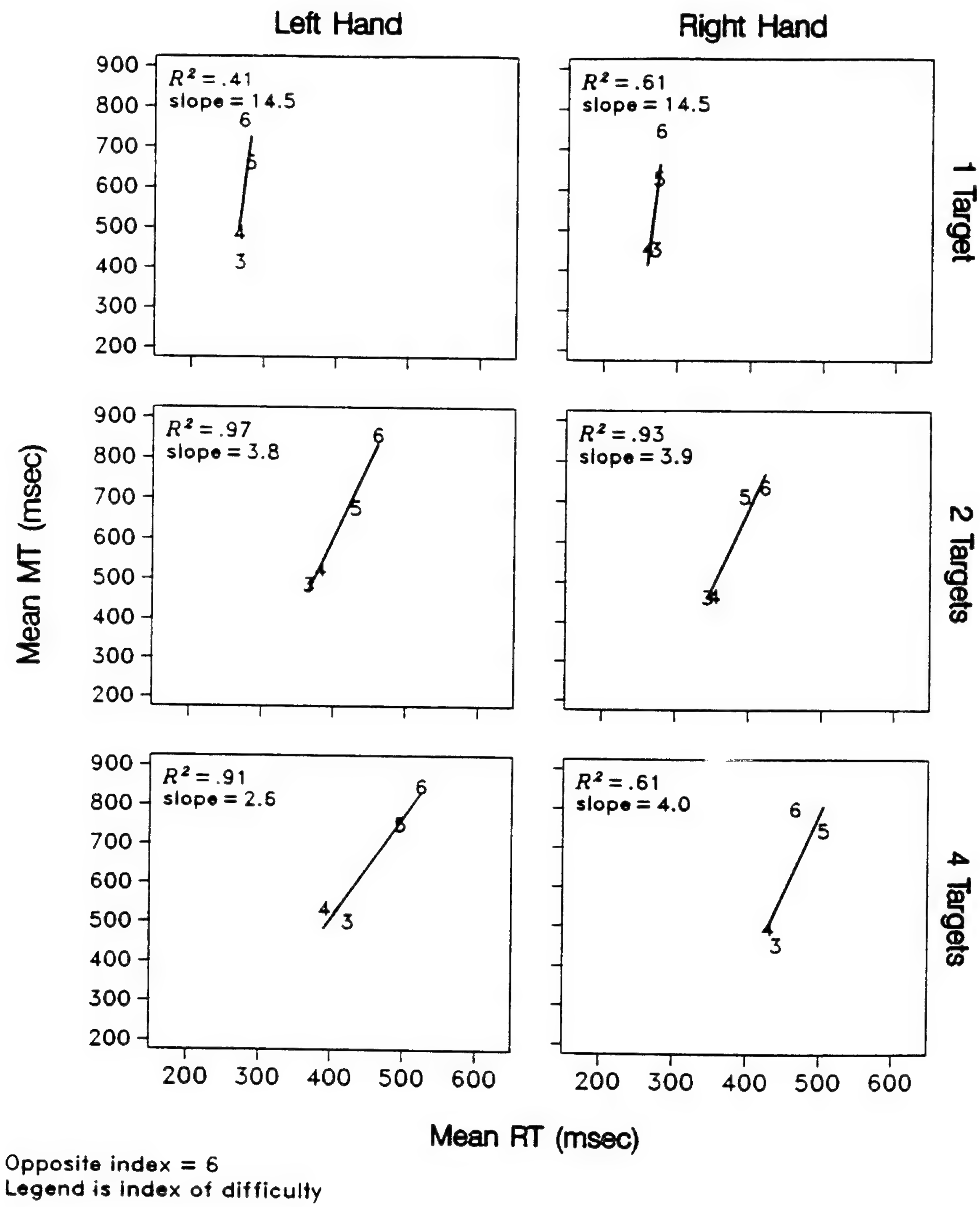



Figure 5.30. MT vs. RT (OPID = 6).

### 5.3.9 Synchrony/Asymmetry

A major issue under the bimanual movement paradigm is whether or not the hands move in a coordinated, synchronous effort, or whether the movement is asynchronous. The two models referenced earlier (coordinative structures as offered by Kelso et al., 1979 and Kelso et al., 1983 and the neural cross-talk model of Marteniuk et al., 1984) were both derived from research of the bimanual paradigm using the simple reaction task. A major difference in this bimanual experiment is that *choice* bimanual aiming was used. From their research on the bimanual simple reaction task, Kelso et al. (1979, 1983) concluded that the hands moved with simultaneity of action where a "tight coordinative coupling" exists. On the other hand, Marteniuk et al. (1984) concluded otherwise and believed that bimanual performance could be better explained by neural interference between contralateral limbs. Both groups believed reaction was synchronous, whereas Marteniuk et al. stated that movement was not.

Based on *mean* RTs, subject reaction to the visual stimuli appeared simultaneous. That is, there was no significant mean timing difference between the left and right hands in departing the home position. This result held under the bimanual equal-ID condition and the bimanual unequal-ID condition. Simultaneous left/right reaction is supportive of a synchronous bimanual model. The synchrony of reaction as a function of ID by OPID and target alternatives can be seen graphically in Figures 5.31 and 5.32. The two figures contain the same information, though displayed differently. Figure 5.31 plots left hand RT as a function of ID by right OPID. Figure 5.32 is the complimentary graph where right hand RT as a function of ID is plotted by left OPID. Notice that the left and

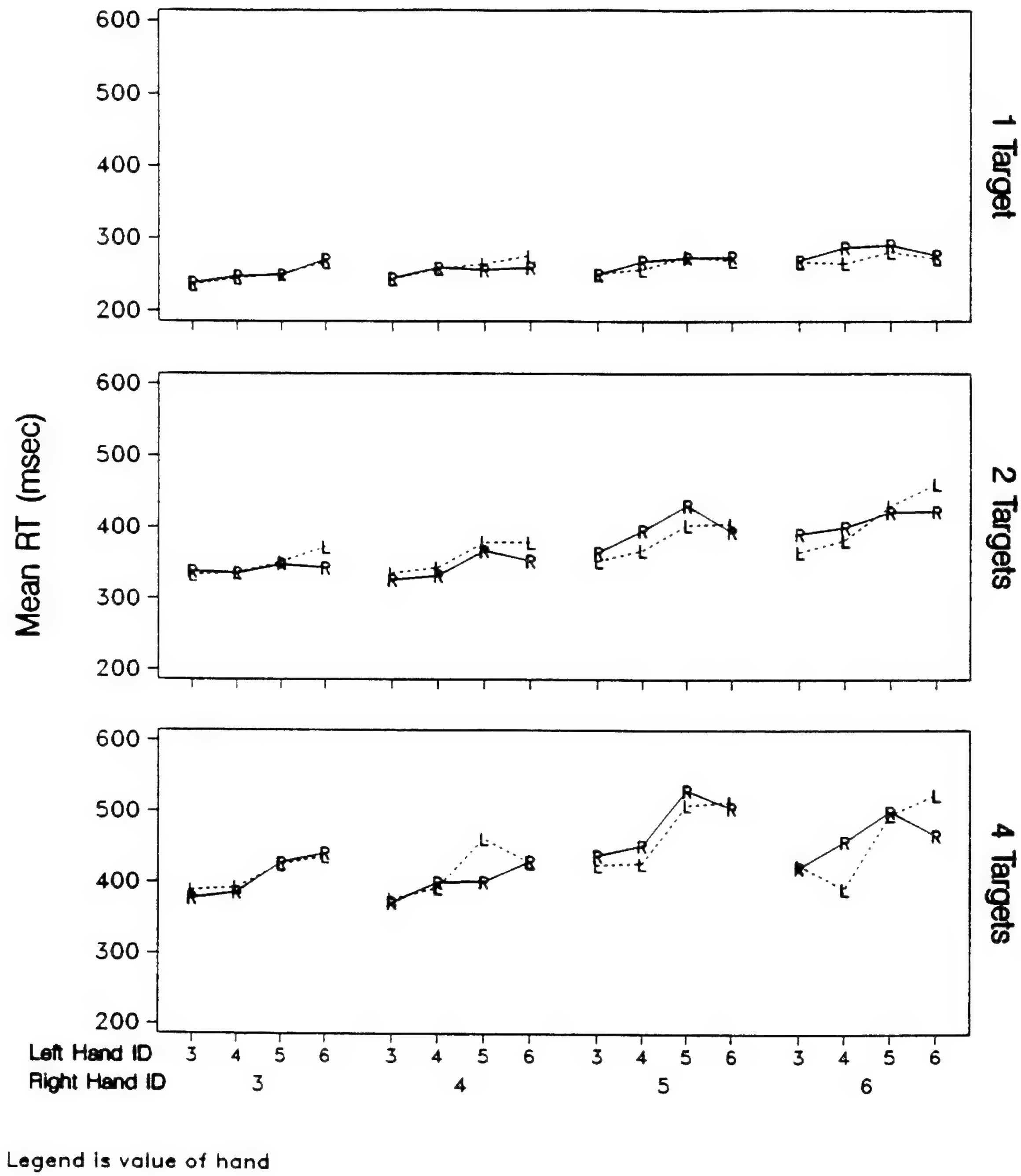



Figure 5.31. Differences in Mean Left Hand/Right Hand RT.

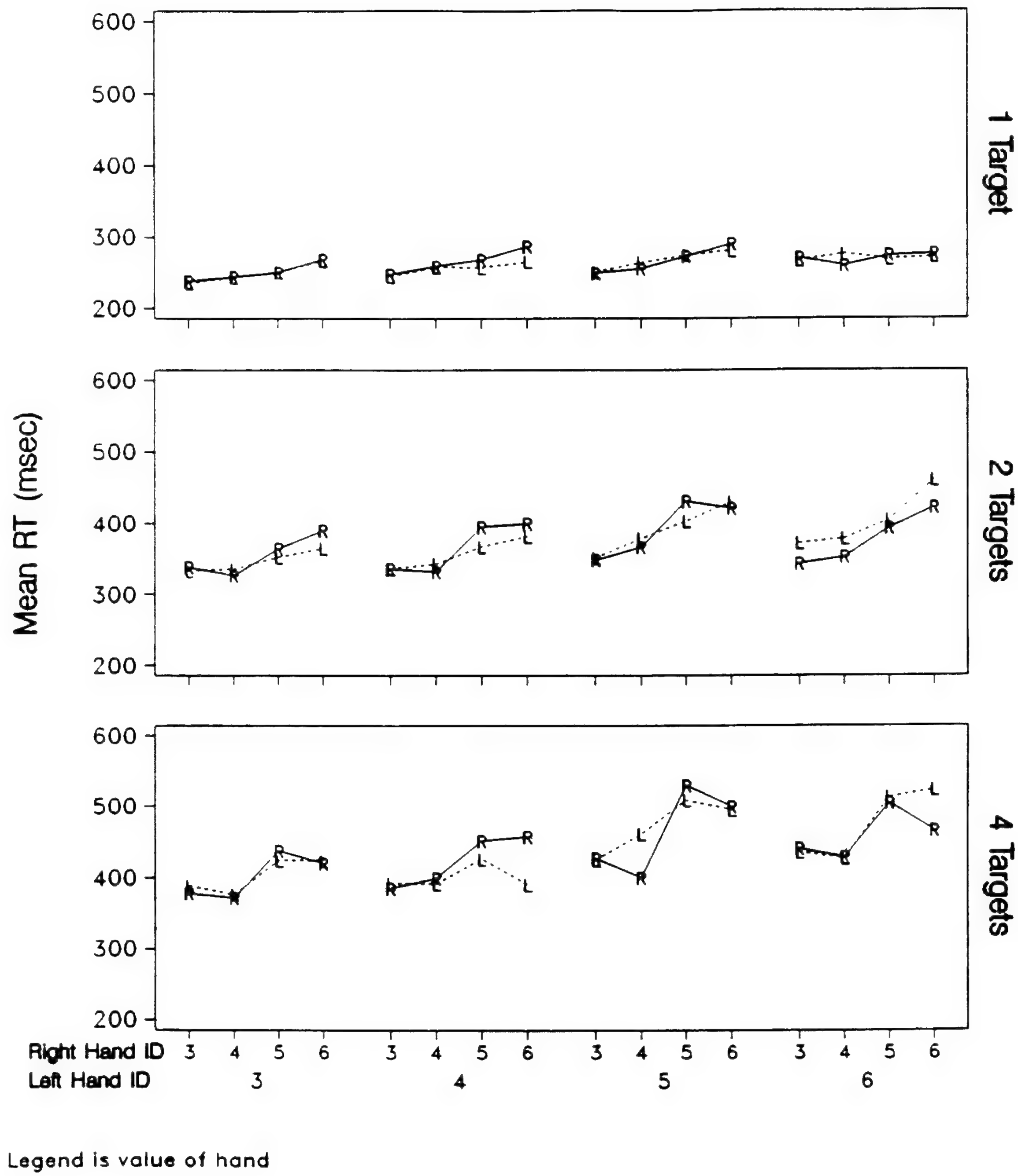



Figure 5.32. Differences in Mean Right Hand/Left Hand RT.

right mean reaction time differences are very small. Contrasts indicated that at only four points did the left and right values differ significantly.

For movement time, averaged over all conditions under the bimanual paradigm, hand effects were **not** significant for any ID tested. On the average, the hands moved equally fast. Post-hoc contrasts indicated, however, that MT was asynchronous in the unequal-ID conditions and generally synchronous in the equal-ID and "near" equal-ID conditions. That is, there was no significant timing difference between hands when each moved to a target of equal (or near equal) ID. This held for all three target alternative sets. However, when the left and right hands moved to targets of differing difficulty (ID difference of two or more), a trend toward significant movement time differences between the hands occurred. This performance asymmetry is represented graphically in Figures 5.33 and 5.34. Figure 5.33 plots left hand MT as a function of ID by right hand OPID, and its compliment, Figure 5.34, plots the right hand MT as a function of ID by left hand OPID for all target alternative conditions. Notice in these two plots that when the hands were moving to targets of equal, or about equal ID, the timing differences were very close, and in general, were not significantly different. However, when the hands moved to targets with IDs differing by two or more, the MT differences between hands became substantial and, in general, were significant. These MT difference graphs show a strong asychrony in mean temporal measures between hands when any asymmetry in task difficulty existed.

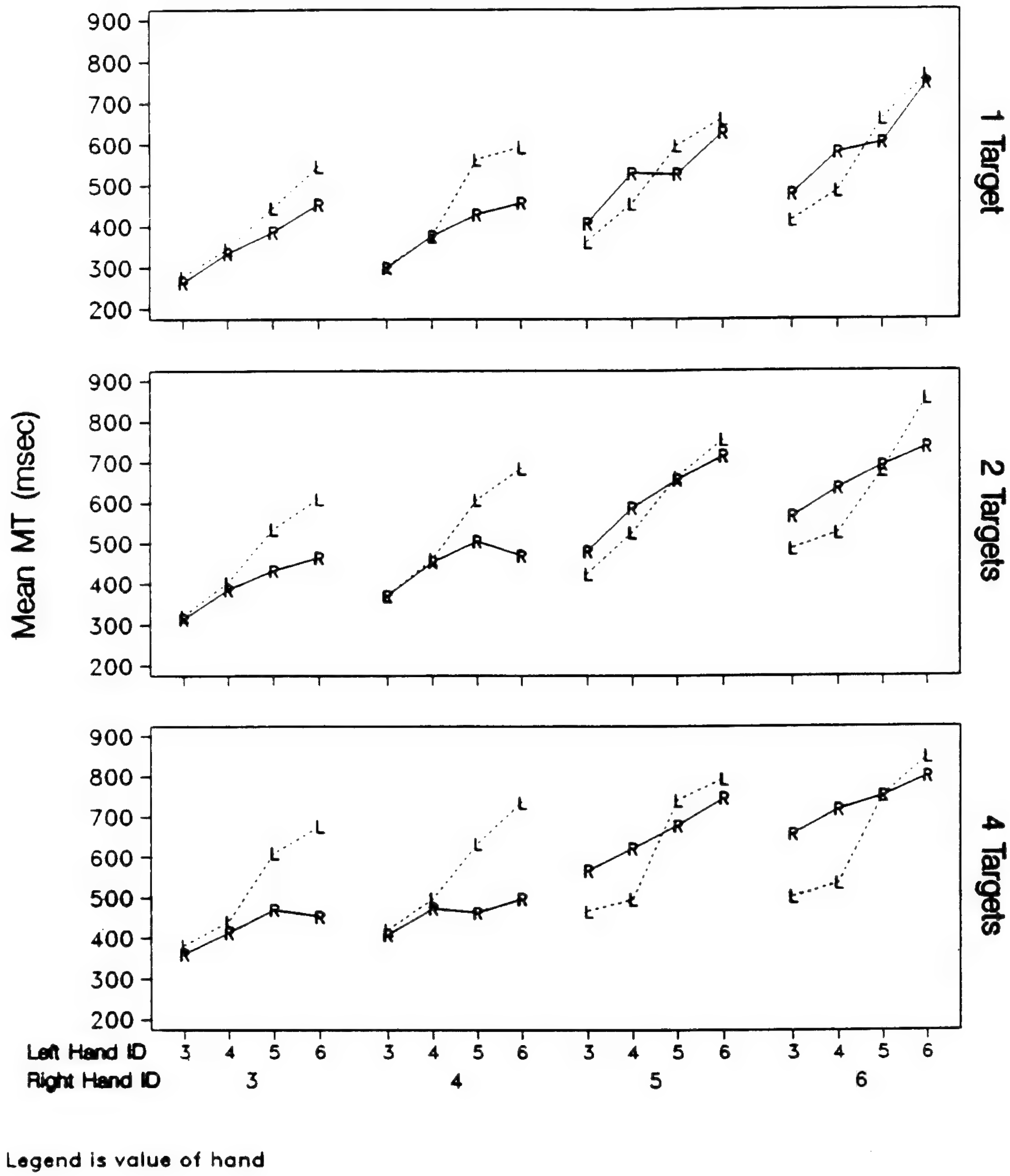



Figure 5.33. Differences in Mean Left Hand/Right Hand MT.

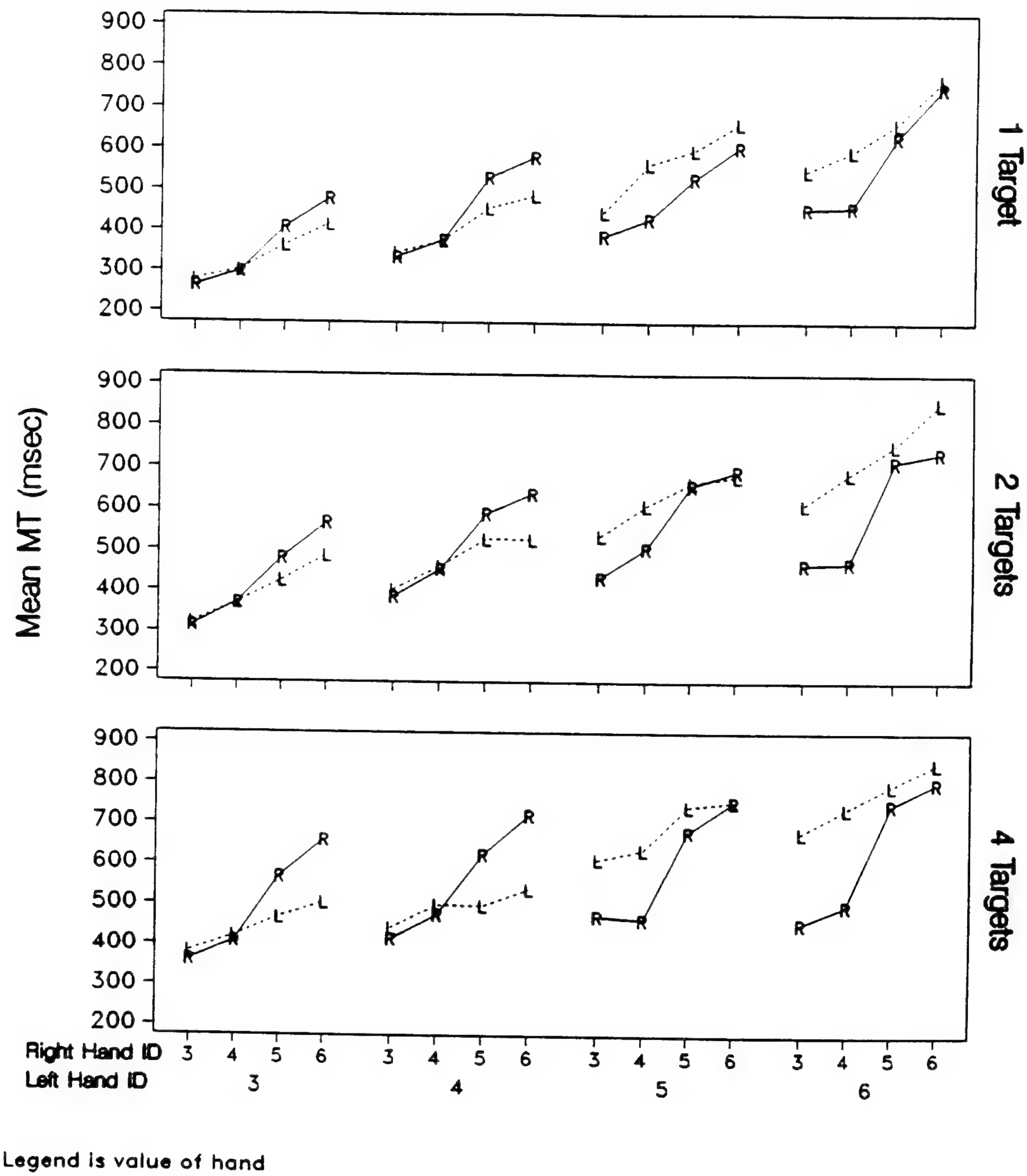



Figure 5.34. Differences in Mean Right Hand/Left Hand MT.

Caution in interpreting Figures 5.31 through Figure 5.34 is needed because mean times are used. Individual subjects usually favored one hand or the other and these differences may be hidden in algebraic cancellation when computing the means. An alternative way of examining the asychrony/asymmetry relationship is now presented. Figure 5.35 plots "Hard ID MT minus Easy ID MT" for various bimanual unequal-ID combinations. Notice that mean hard minus easy MT differences for the 3-4 condition are very small across all target alternative conditions. The only substantial negative value occurred at ID = 5/6, N = 1, indicating that the left, easy hand had a longer MT than the relatively harder right hand. In this rare instance, the harder target hand moved faster than the easier target hand. In all other cases, the hard target hand took longer to get to the target. In general, the timing difference was larger when the left hand moved to the hard target.

Another way to view synchrony is in terms of absolute time differences between the hands. Figure 5.36 shows the mean absolute reaction time difference between the hands for the equal-ID and unequal-ID conditions. The ID units marked on the abscissa progress from an ID difference of zero (equal-ID) to two and finally three at the 3-6 condition. The pattern of results is not particularly clear except for the increase beyond the 3-3 and 3-4 conditions.

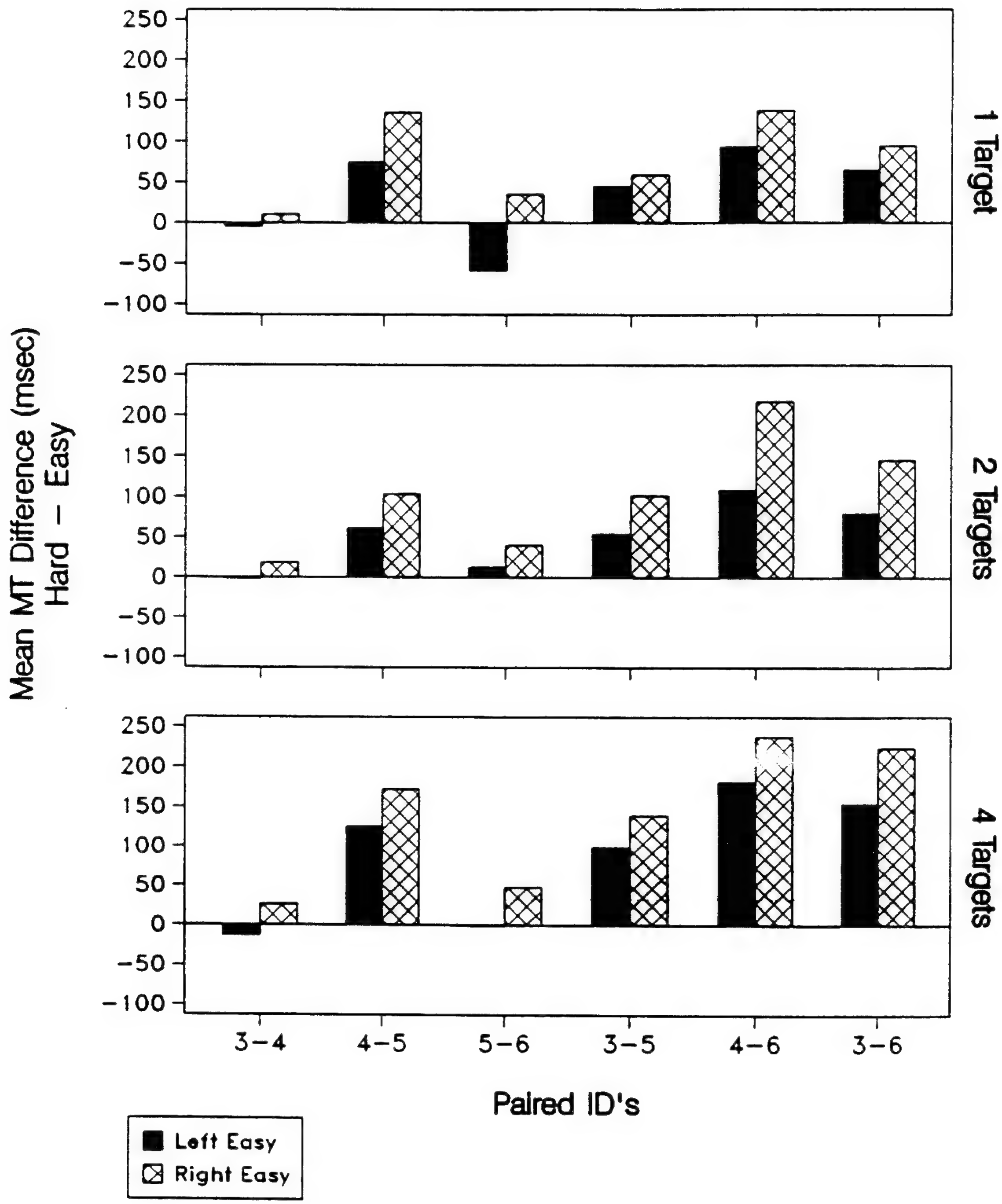



Figure 5.35. Hard Target Minus Easy Target MT Differences.

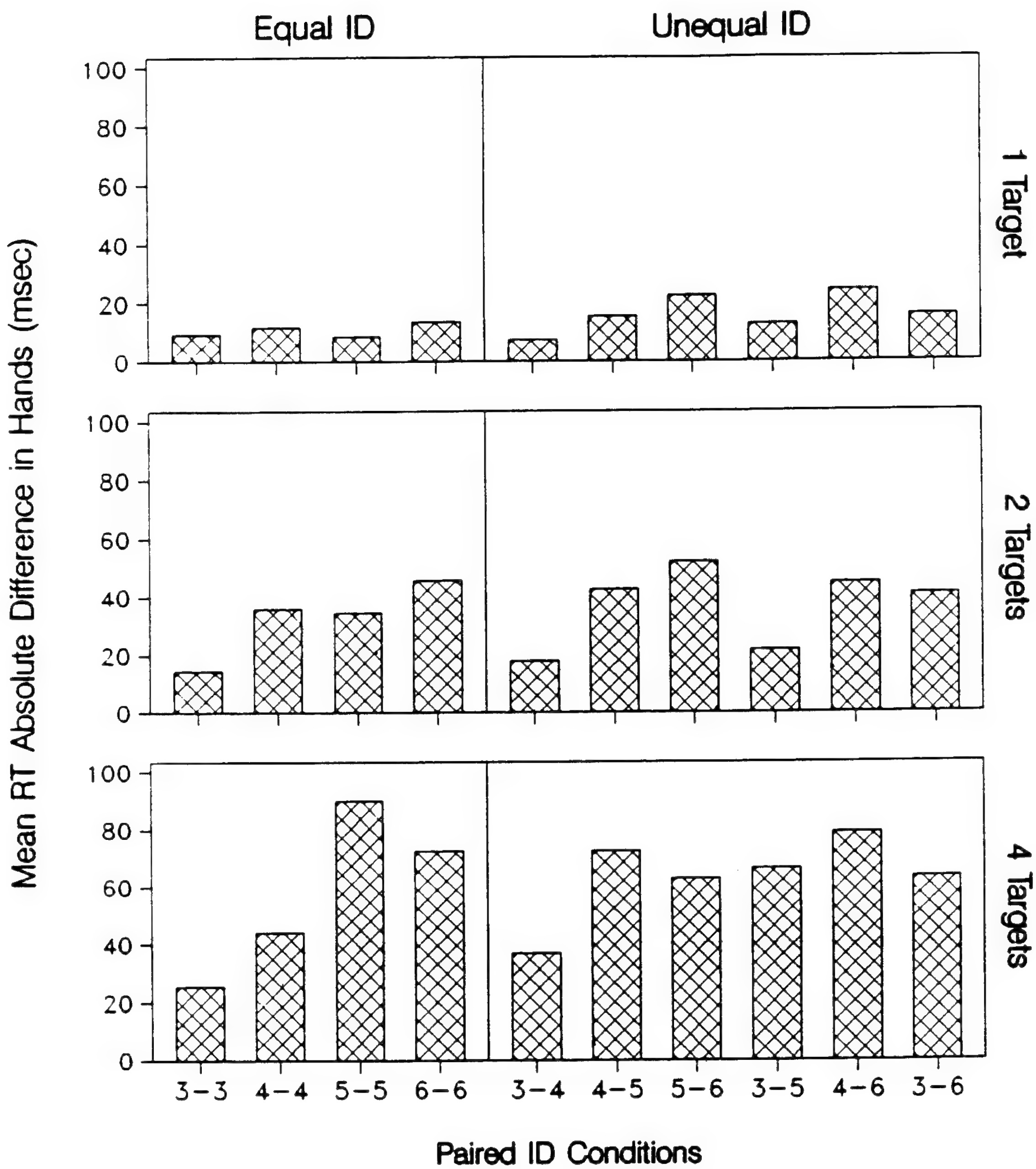



Figure 5.36. Mean Absolute RT Difference Between Hands.

Figure 5.37 plots mean absolute movement time differences. Here a steady progression of increasing differences occurred across increasing equal-ID conditions and across increasing target alternative levels. At the 6-6 ID condition across all target alternative sets, the mean absolute difference equaled or exceeded 200 milliseconds. A 200 millisecond mean absolute difference in hand movement time is substantial, especially for an equal-ID condition. This suggests that as ID increased, subjects concentrated on one hand or the other, letting the performance of the contralateral limb suffer. It may be that subject task strategy played an important role where one hand was neglected until the subject was reasonably assured of success on the other. Figure 5.37 presents a strong argument against movement synchrony and suggests that it is not the symmetry of task difficulty but rather the tasking of the contralateral limb with increasing difficulty that accounts for the performance behaviors observed.

To further examine large MT differences between the hands, the percentage of subjects with left hand/right hand MT differences greater than 100 milliseconds[6] was determined (Figures 5.38 through 5.40). Each five percent is approximately equal to one subject. In general, a large percentage of the subjects had left/right movement time differences greater than 100 milliseconds. For example, for IDL/IDR = 6/6 and N = 1, 52.6% of the subjects had left/right movement time differences greater than 100 milliseconds (31.6% with the left hand slower and 21.0% with the right hand slower).

[6]The 100 millisecond threshold was chosen arbitrarily but was thought to be large enough to show whether a difference in difficulty of one hand or the other occurred.

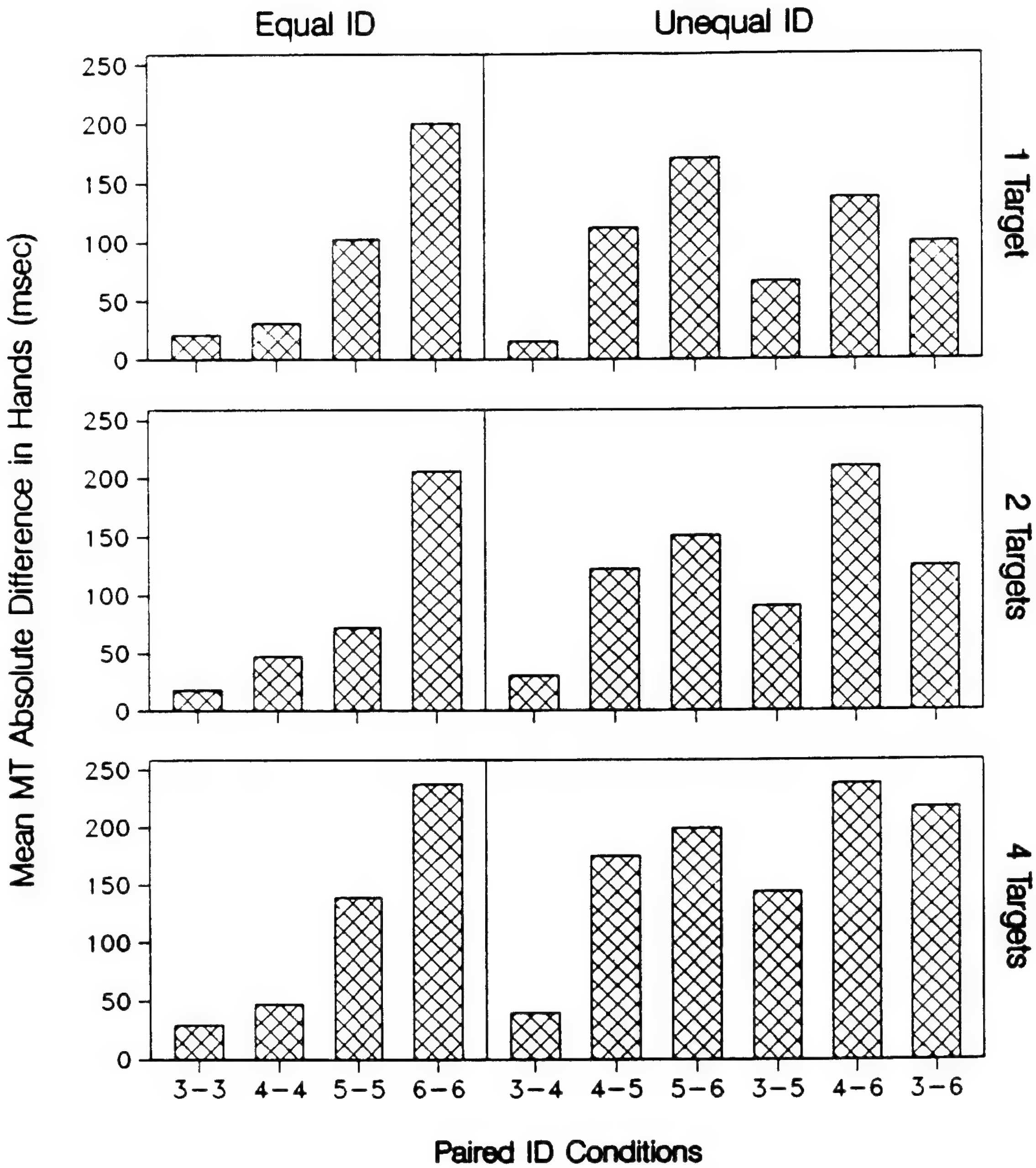



Figure 5.37. Mean Absolute MT Difference Between Hands.

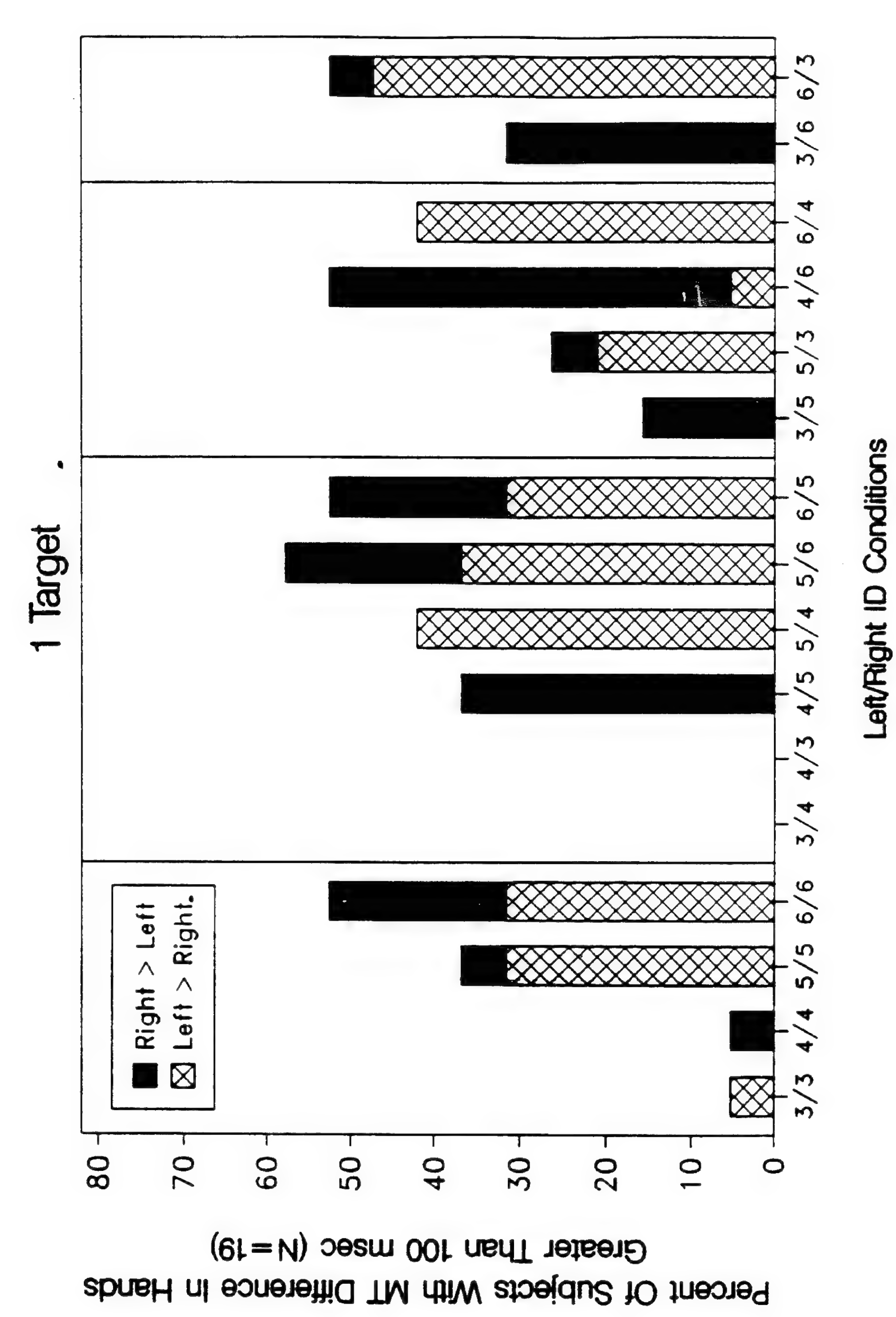



Figure 5.38. Percent Subjects with Hand MT Differences > 100 msec (N = 1).

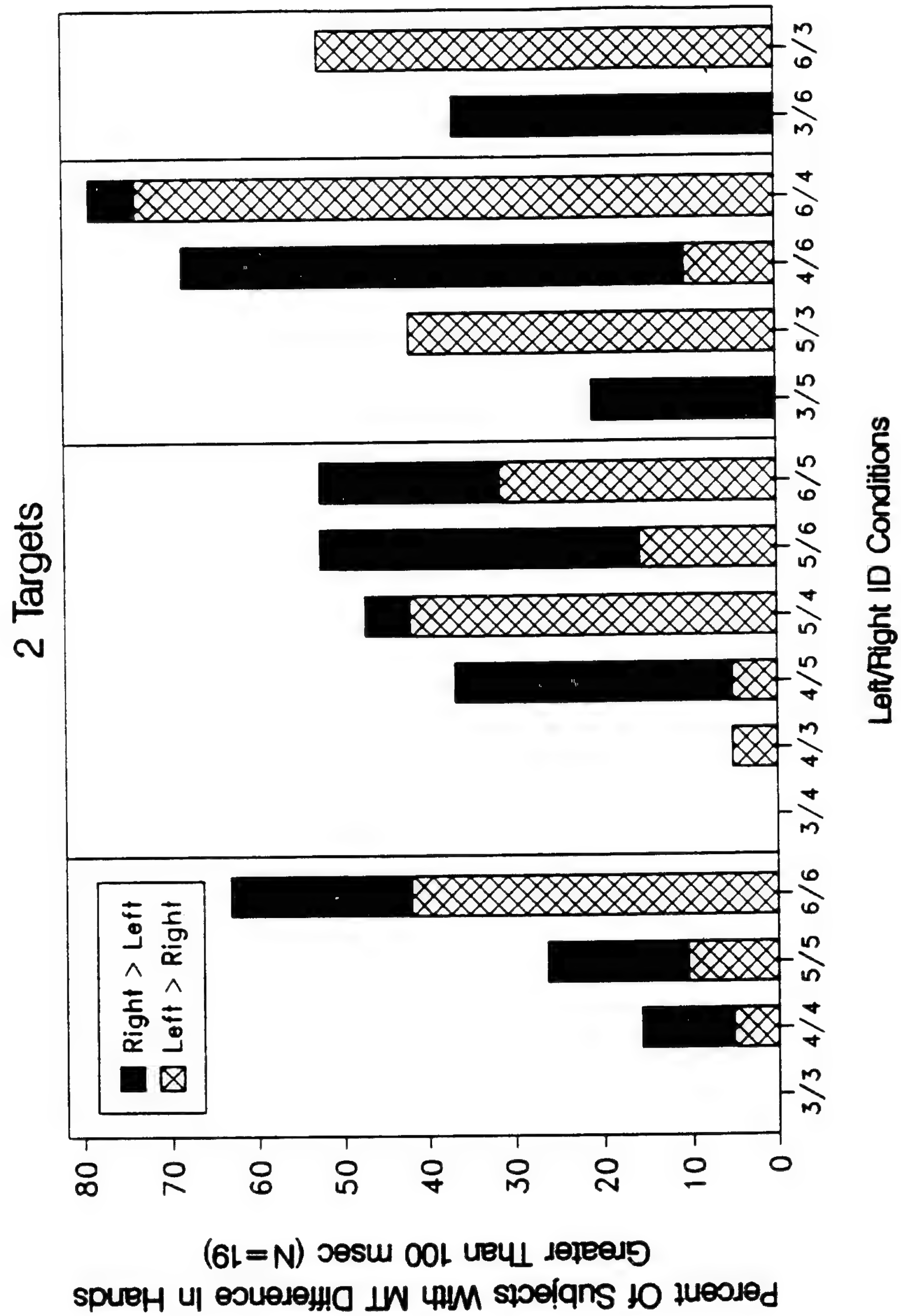



Figure 5.39. Percent Subjects with Hand MT Differences > 100 msec (N = 2).

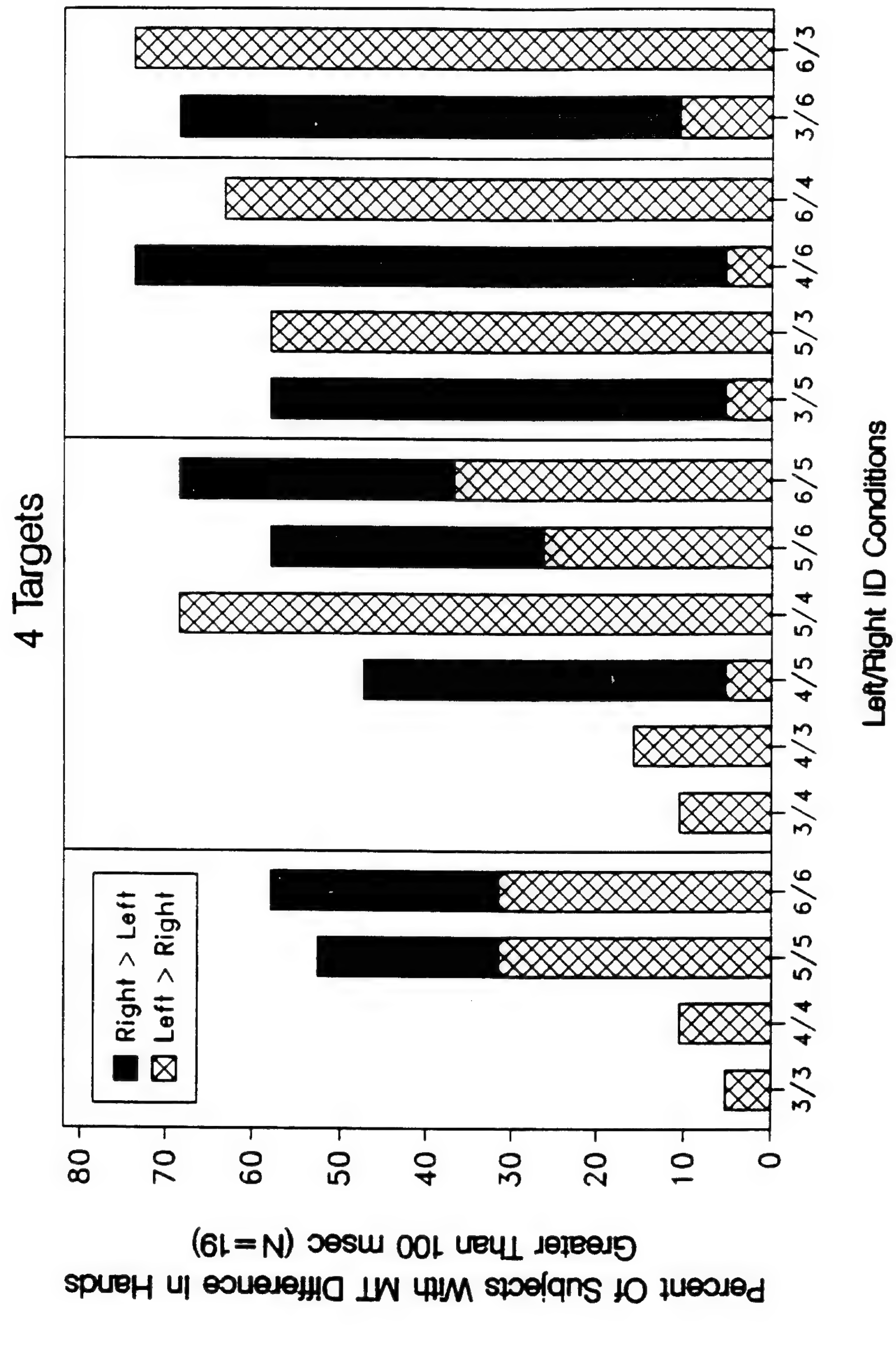



Figure 5.40. Percent Subjects with Hand MT Differences > 100 msec (N = 4).

## 5.4 Performance Models

Bimanual aiming performance models for RT, MT and total response time were tested. Because of the strong effect of the opposite task ID, it seemed appropriate to include OPID as a factor when modeling bimanual performance. Before the models were tested, OPID was tested for linear, quadratic and cubic effects on MT at each ID level. Table 5.23 presents the $F$ and $p$ values for these tests. As presented, OPID had a highly significant linear effect at each ID. Only at ID = 4 did a quadratic effect reach significance. Since a quadratic effect was only found at one ID and since no significant cubic effects occurred, linear models of RT, MT and total response time (TRT) as functions of $H_s$, ID and OPID were developed. The best RT, MT, and TRT models would be simple, and generalizable to the unimanual condition.

Since both RT and MT are adequately modeled from information theoretic bases, and since each is a function of a variable measured in bits, it would be highly desirable to have an overall total response time model that combined reaction time and movement time. The best model would be simple and would explain a relatively large amount of the response time variation as measured by the coefficient of determination. As reported earlier, Beggs et al. (1972) concluded that a linear combination of Hick's Law and Fitts' Law was inappropriate from their data since MT was found to be a function of the number of target alternatives. In their opinion, this violated Fitts' Law and their assumption that sequential information processing was taking place.

Stepwise regression (Draper and Smith, 1981) was conducted on the unimanual data in isolation, the bimanual data in isolation and the combined unimanual and

bimanual data to find the best variables for predicting RT, MT and TRT. The candidate variables were stimulus information ($H_s$) and index of difficulty (ID) plus opposite hand ID (OPID) for the bimanual and combined data.

Table 5.23. Linear, Quadratic and Cubic OPID Effects.

| **Effect** | ***F*-value** | ***p*-value** |
|---|---|---|
| **ID = 3** | | |
| Linear | 36.42 | 0.0001 |
| Quadratic | 1.49 | 0.24 |
| Cubic | 0.30 | 0.59 |
| **ID = 4** | | |
| Linear | 18.38 | 0.0004 |
| Quadratic | 7.75 | 0.012 |
| Cubic | 0.00 | 1.00 |
| **ID = 5** | | |
| Linear | 42.12 | 0.0001 |
| Quadratic | 1.97 | 0.18 |
| Cubic | 0.59 | 0.45 |
| **ID = 6** | | |
| Linear | 71.57 | 0.0001 |
| Quadratic | 0.96 | 0.34 |
| Cubic | 1.85 | 0.19 |

For the unimanual RT, MT and TRT data, stepwise regression selected $H_s$ and ID as necessary predictor variables for all models. Thus, the best unimanual performance models are given by:

$$Time = \beta_0 + \beta_1 \cdot H_s + \beta_2 \cdot ID. \tag{23}$$

Table 5.24 presents the values of the coefficients for each model along with the respective coefficients of determination.

Table 5.24. Unimanual Performance Model Coefficients.

| Unimanual Data | | | | |
|---|---|---|---|---|
| | $\beta_0$ | $\beta_1$ | $\beta_2$ | $R^2$ |
| **RT** | 171.2 | 27.2 | 6.9 | 0.95 |
| **MT** | -71.2 | 21.6 | 86.5 | 0.96 |
| **TRT** | 99.9 | 48.8 | 93.4 | 0.97 |

For the bimanual RT, MT and TRT data, stepwise regression selected $H_s$, ID and OPID as the best predictor variables. Thus, the best bimanual performance models are given by:

$$Time = \beta_0 + \beta_1 \cdot H_s + \beta_2 \cdot ID + \beta_3 \cdot OPID. \tag{27}$$

Table 5.25 presents the values of the coefficients for each model along with the

respective coefficients of determination.

Table 5.25. Bimanual Performance Model Coefficients.

| Bimanual Data | | | | | |
|---|---|---|---|---|---|
| | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $R^2$ |
| **RT** | -6.6 | 131.0 | 19.3 | 14.0 | 0.90 |
| **MT** | -299.2 | 76.0 | 104.1 | 53.9 | 0.95 |
| **TRT** | -305.7 | 206.9 | 123.4 | 67.9 | 0.94 |

For the unimanual and bimanual combined RT data, stepwise regression selected $H_s$, ID and OPID. Thus, the best unimanual/bimanual combined performance models are given by:

$$Time = \beta_0 + \beta_1 \cdot H_s + \beta_2 \cdot ID + \beta_3 \cdot OPID. \tag{28}$$

Table 5.26 presents the values of the coefficients for each model along with the respective coefficients of determination.

Table 5.26. Combined Performance Model Coefficients.

| Combined Unimanual and Bimanual Data | | | | | |
|---|---|---|---|---|---|
| | $\beta_0$ | $\beta_1$ | $\beta_2$ | $\beta_3$ | $R^2$ |
| **RT** | -0.2 | 110.2 | 16.9 | 22.1 | 0.84 |
| **MT** | -216.9 | 65.1 | 100.6 | 43.7 | 0.95 |
| **TRT** | -217.1 | 175.3 | 117.4 | 65.8 | 0.93 |

For RT, the $R^2$ is greater when based on the bimanual data in isolation compared with the combined data. Thus, it is recommended that RT be modeled separately for the unimanual and bimanual tasks. The models for MT and TRT, however, show little difference between the bimanual and the combined data sets. For modeling MT or TRT, therefore, it is not necessary to separate the unimanual and bimanual tasks.

For bimanual movement, $H_s$ is a greater contributor than ID or OPID individually with respect to total response time. An increase of 1 bit in $H_s$ produces a greater increase in TRT than a one-bit increase in ID. All coefficients for the TRT model are precisely the sum of the corresponding coefficients in the RT and MT models.

# CHAPTER VI

## DISCUSSION

The results from Pilot Study I verified that RT was a function of the number of target alternatives (N) as predicted by Hick's Law, and that MT was a function of ID as predicted by Fitts' Law. However, ID was also shown to have a significant effect on RT, and N was shown to have a significant effect on MT. LED stimulus presentation resulted in significantly shorter MT values. Greater ID x $H_S$ interaction occurred with CRT presentation for both RT and MT than with LED presentation. Differences in visual scanning requirements between the two conditions probably accounted for the performance differences observed. Using the CRT as the presentation medium, subjects had to scan the CRT for the stimulus event, then move their eyes and scan the target board to find the appropriate target. Occasionally, subjects looked back to the CRT for stimulus verification before hitting the target.

With respect to RT, Pilot Study II showed that the unimanual condition was faster than the bimanual condition, that the unimanual left hand reacted faster than the right, and that RT depended on the number of targets *and* the index of difficulty. The MT results of Pilot Study II showed that the right hand moved faster than the left, that MT increased with increasing ID, *and* with increasing number of target alternatives. Pilot Study II also demonstrated that the bimanual Stimulus-Response Board was an appropriate apparatus to measure bimanual performance and served as a test-bed for the

controlling software.

## 6.1 Main Study Unimanual Study

Unimanual reaction time results are summarized as follows:

- RT increased as N increased
- RT increased as ID increased
- Left hand reacted faster than the right.

Unimanual movement time results are summarized as follows:

- MT increased as ID increased
- MT increased as N increased
- Right hand moved faster than the left.

Unimanual RT was adequately modeled by Hick's Law. That is, RT increased linearly with the amount of stimulus information as defined by Hick (1952) provided ID was held constant. RT was also found to depend on Fitts' index of difficulty. The ID effect on RT was also strong in Pilot Studies I and II. For this reason, it is difficult to evaluate the model for RT strictly in terms of the number of target alternatives since RT is not solely a function of the number of target alternatives. Table 6.1 presents RT coefficient of determination values ($R^2$) for the Main Study conditions tested at fixed ID and OPID. The unimanual conditions are represented by OPID = NONE.

With respect to unimanual RT, the left hand reacted faster than the right (244 vs. 250 msec) although the difference has little practical significance in most situations. This result, though somewhat unexpected, was consistent with Pilot Studies I and II. Because

Table 6.1. RT and MT R-Square Values.

R-SQUARED FOR FIT OF REACTION TIME (HICK'S LAW)

| OPPOSITE INDEX OF DIFFICULTY | ID 3 | ID 4 | ID 5 | ID 6 |
|---|---|---|---|---|
| NONE | 0.96 | 0.95 | 0.98 | 0.94 |
| 3 | 0.93 | 0.95 | 0.97 | 0.91 |
| 4 | 0.94 | 0.98 | 0.95 | 0.93 |
| 5 | 0.98 | 0.91 | 0.97 | 0.97 |
| 6 | 0.99 | 0.91 | 0.97 | 0.88 |

R-SQUARED FOR FIT OF MOVEMENT TIME (FITTS' LAW)

| OPPOSITE INDEX OF DIFFICULTY | 1 TARGET | 2 TARGETS | 4 TARGETS |
|---|---|---|---|
| NONE | 0.96 | 0.97 | 0.96 |
| 3 | 0.98 | 0.99 | 0.96 |
| 4 | 0.94 | 0.98 | 0.98 |
| 5 | 0.99 | 0.98 | 0.89 |
| 6 | 0.95 | 0.93 | 0.93 |

the right hand was preferred by all participants, subjects may have concentrated on non-dominant hand movement (left hand) and adapted their efforts to compensate for a slow MT with a faster RT. Danev et al. (1971) examined aiming behavior under stressed and non-stressed conditions and found that subjects were able to estimate RT and adapt MT as needed to maintain a consistent total response time. It may be that subjects can also adapt RT to MT in similar fashion.

For fixed N, movement time increased linearly with increasing ID, supporting Fitts' Law. Movement time also increased with an increasing number of target alternatives which confounds any effort to evaluate movement performance solely in terms of index of difficulty. Table 6.1 presents MT $R^2$ values for the Main Study at fixed N and OPID (unimanual conditions as OPID = NONE). The right hand unimanual MT was significantly faster than the left hand MT (235 vs. 372 msec).

**6.2 Unimanual vs. Bimanual Equal-ID**

Unimanual vs. bimanual equal-ID RT results may be summarized as follows:

- Unimanual reactions were faster than bimanual
- RT increased as N increased
- RT increased as ID increased
- No significant left/right difference in RT means
- Unimanual - bimanual differences increased with N and ID.

Unimanual vs. bimanual equal-ID MT results are summarized as follows:

- Unimanual movements were faster than bimanual

- MT increased as ID increased
- MT increased as N increased
- Right hand moved faster than the left
- Unimanual-bimanual MT differences increased with N and ID.

Unimanual RTs were significantly shorter than RTs for the corresponding bimanual equal-ID condition. Under the bimanual equal-ID conditions, RT increased with increasing N *and* ID. The magnitude of the unimanual vs. bimanual RT difference increased with increasing N and with increasing ID. No significant mean RT difference between the left and right hands was found. The mean absolute left/right RT difference between the hands increased as N increased (Figure 5.36).

Movement time was significantly shorter for unimanual movements than for the corresponding bimanual equal-ID conditions (353 vs. 550 msec). MT increased with increasing ID *and* N. As with RT, the harder the task in terms of N or ID, the greater was the difference between the unimanual and bimanual MT performance. The right hand was significantly faster (434 vs. 469 msec) under the bimanual equal-ID conditions. Significant MT differences between the hands suggest that the movements were not synchronized.

### 6.3 Bimanual Unequal-ID

Bimanual unequal-ID performance results may be summarized as follows:

- RT and MT increased as N increased
- RT and MT increased as ID increased

- RT and MT varied as OPID and N varied.

Under the bimanual unequal-ID conditions, RT increased with increasing N as expected. RT also increased as a function of increasing ID and increasing task difficulty of the opposite hand (OPID). There were no RT differences between hands, which suggests a left/right reaction synchrony, with longer RTs as N, ID, and OPID increased.

Movement time under the bimanual unequal-ID paradigm was affected by N, ID and OPID. *For all conditions*, MT increased as OPID increased (Figure 5.20). Table 6.2 presents left/right movement times for four cases in terms of IDL and IDR represented as easy/hard. The four cases are: Case 1: easy/easy, Case 2: easy-hard; Case 3: hard/easy; and Case 4: hard/hard. Notice that in comparing all cases, if OPID changes, then MT changes in the same direction.

It may be that for a very easy task, any time the contralateral limb is active, performance is significantly affected because movement time is initially short for an easy task. However, for a very difficult task, movement time is already large and tasking the opposite limb has less impact on the hard task. A hard task is always hard. Making it harder results in a proportionally smaller change than when an easy task is made harder.

Table 6.2. Bimanual Equal-ID vs. Unequal-ID MT.

| Case 1 Easy/Easy | Case 2 Easy/Hard | Case 3 Hard/Easy | Case 4 Hard/Hard |
|---|---|---|---|
| **3/3** | **3/6** | **6/3** | **6/6** |
| 329/314 | 469/568 | 613/458 | 825/762 |
| | | | |
| **3/3** | **3/5** | **5/3** | **5/5** |
| 329/314 | 419/485 | 613/458 | 668/662 |
| | | | |
| **3/3** | **3/4** | **4/3** | **4/4** |
| 329/314 | 366/359 | 397/379 | 446/435 |
| | | | |
| **4/4** | **4/5** | **5/4** | **5/5** |
| 446/435 | 494/581 | 603/476 | 668/662 |
| | | | |
| **4/4** | **4/6** | **6/4** | **6/6** |
| 446/435 | 517/645 | 673/476 | 825/762 |
| | | | |
| **5/5** | **5/6** | **6/5** | **6/6** |
| 668/622 | 698/683 | 738/697 | 825/762 |

### 6.4 Hand Synchrony

Based on the results of the RT and MT timing differences, a major factor determining response time performance was task difficulty of the opposite hand (OPID). Even though there was no significant main effect of hand on RT, large mean absolute left/right RT differences occurred under all bimanual conditions (Figure 5.36). These results suggest that, even for equal-ID conditions, reactions were, in fact, not synchronized.

The OPID effect extends to MT performance where significant differences occurred when the task ID of the opposite hand increased. Even the bimanual equal-ID conditions showed little MT synchrony. For example, the mean absolute difference between hands was greater than 200 milliseconds at the 6/6 condition (Table 5.37) where a large percentage (25+%) of the subjects demonstrated MT differences greater than 100 milliseconds (Figure 5.40).

### 6.5 Six Research Questions Answered

The following six points were addressed in this research as presented in the Problem Statement (Section 1.6).

#### 6.5.1 Does Hick's Law Hold Under the Bimanual Paradigm?

Hick's Law does hold under bimanual equal-ID and unequal-ID conditions. Coefficients of determination ($R^2$) obtained using RT data averaged across subjects and hands and regressed on stimulus information $H_s$ ($H_s = \log_2(N+1)$) for each ID and

OPID combination confirm that a large percentage of RT variance was accounted for by Hick's model (Table 6.1). Specifically, for each hand, ID, and OPID, RT increased linearly (as predicted by Hick's Law) as a function of $H_S$ (Figures 5.6 - 5.10). The range of $R^2$ values was 0.88 to 0.99.

### 6.52 Does Fitts' Law Hold Under the Bimanual Paradigm?

Fitts' Law does hold under the bimanual equal-ID and unequal-ID conditions. Coefficients of determination ($R^2$) obtained using MT data averaged across subjects and regressed on ID for each hand, N, and OPID combination confirm that a large percentage of the MT variance was accounted for by Fitts' model (Figures 5.14 - 5.18, Table 6.1). The range of $R^2$ values was 0.89 to 0.99. When N and OPID were held constant and ID was varied, MT could be expressed as a linear function of ID ($ID = log_2\,(2 \cdot A/W)$). The fact that MT remained a linear function of ID under bimanual movements is the basis for concluding that Fitts' Law is valid even though a shift toward longer movement times occurred when the contralateral limb was added.

Fowler et al. (1991) compared each unequal-ID condition separately with its bimanual equal-ID counterpart and found condition to be significant only at ID = 0.77. That is, only the easy target, when paired with opposite targets of increasing difficulty, showed significance when comparing the bimanual equal-ID and bimanual unequal-ID conditions. From this, they concluded that Fitts' Law was violated only for the easy ID target. If this is interpreted to mean that MT cannot be predicted directly from

$log_2 (2 \cdot A/W)$ using the same y-intercept and slope, then this probably correct (from their results). Other factors (N and OPID) influence bimanual performance to change the slope and intercept parameters. If MT is only shifted upward (toward slower movements) as the opposite task ID increases, or if the MT slope changes, then performance may still obey Fitts' Law but with a change in the parameters defining the linear relationship between MT and ID as OPID changes (Figure 5.19).

**6.53 How Do Bimanual Simple Reaction Tasks and Choice Reaction Tasks Differ?**

The unimanual vs. bimanual condition effect and the ID effect on RT and MT under the simple reaction paradigm were found to be amplified under the choice reaction paradigm. As shown in Figure 5.2, bimanual mean RT plotted as a function of ID and collapsed across all other conditions except the number of target alternatives, increased as N increased from one to two to four. The significant COND x N x ID interaction (Table 5.12) suggests that as ID changed, the combined effect of N and COND varied. Indeed, from Figure 5.2 it can be seen that RT increased with increasing $H_S$ and this effect was amplified with increasing ID. Similarly, the difference between the unimanual and bimanual conditions became greater as N increased. As ID increased (holding OPID constant), the effect of increasing the number of target alternatives was much greater under bimanual conditions that-under unimanual conditions (Figure 5.4).

Increasing the number of target alternatives clearly shifted MT toward longer times under bimanual conditions compared with unimanual movements. MT also showed an upward shift under unimanual conditions with increasing ID (Fitts' Law). However,

this shift in slope was much smaller in magnitude for the unimanual task than for the bimanual task. The MT difference between the number of target alternatives was not as clearly defined for the unimanual task as for the bimanual task (Figure 5.13). The significant COND x N interaction (Figure 5.12) confirmed that as the number of target alternatives increased, the difference between unimanual and bimanual MT performance increased.

### 6.5.4 How Are RT and MT Correlated Under the Bimanual Paradigm?

Reaction times and movement times were positively correlated for all bimanual tasks across all subjects, hands, target alternative levels, IDs, and OPIDs ($r = 0.97$). That is, long RTs were associated with long MTs and short RTs were associated with short Mts. Since RT and MT are both dependent on N, ID and OPID, a high covariance between the two performance measures is not surprising.

### 6.5.5 Did the Limbs Act In synchrony?

Under bimanual equal-ID and unequal-ID conditions, no significant left/right hand effects on RT were found. Figures 5.31 and 5.32 showed mean left and right hand reaction times as a function of ID for various OPID values. These figures suggest that the left and right hands departed the home positions simultaneously. However, Figures 5.31 and 5.32 must be viewed with caution because limb asynchrony may be hidden in the averaging of left and right RTs across subjects and conditions. That is, due to algebraic cancellation, any existing left/right differences may be lost. This washing out

of RT differences can occur within and between subjects. If subjects reacted more quickly one time with the left and the next time with the right, then the effects of these timing differences may cancel when computing the average. Similarly, if one subject favored one hand over the other and another subject did the opposite, then these left/right timing differences may cancel.

Alternatively, Figure 5.36 presents the mean absolute bimanual RT differences. From this plot, under the N = 1 condition, most absolute differences were less than 20 milliseconds. However, with increasing N, the majority of mean absolute differences was well above 20 milliseconds. Notice that the mean absolute difference between hands at N = 2 and IDL/IDR = 5/5 was approximately 40 milliseconds, while at N = 4 and IDL/IDR = 5/5, it was approximately 90 milliseconds. When viewed from the perspective of absolute differences between hands, the subjects did not depart the home positions simultaneously even for the bimanual equal-ID conditions.

Movements were definitely not synchronized based on analysis of the MT data. Figures 5.33 and 5.34 present mean left/right MTs by ID with OPID held constant. From these plots it seems that when ID and OPID were similar (ID-OPID) difference = 1 or less), mean left/right MTs did not differ. When an ID-OPID asymmetry existed (ID-OPID difference greater than 1), mean left/right MTs were significantly different. As with the RT left/right mean difference plots discussed above, these figures may hide differences due to algebraic cancellation. Absolute left/right MT differences are presented in Figure 5.37. Based on significant left/right effects on MT and because of the large mean absolute differences between hands, it can be said that synchronized hand movement did not occur.

### 6.5.6 Can Bimanual Models of RT, MT and Total Response Time be Derived?

Beggs et al. (1972) found that the speed-accuracy trade-off was a function of the number of target alternatives and for this reason concluded that sequential information processing was not occurring and, therefore, Hick's Law and Fitts' Law could not be added linearly to predict total response time. Alternatively, if coding for the movement occurs during the cognitive stages associated with RT, then it is reasonable to find RT to be a function of ID (i.e., the more difficult the movement, the more coding must occur). Similarly, the number of targets may affect MT because the more targets there are, the more the subject must concentrate on hitting the correct target as the movement is taking place. That is, come form of visual and/or proprioceptive feedback mechanism may exist requiring continuous information processing during movement execution. With such a process, more targets implies that more feedback information must be transmitted, and with it, an increased delay associated with the time necessary to process the information. MT would therefore be a function of ID and the number of target alternatives.

With the dependency of reaction time and movement time on N, ID and OPID in mind, bimanual RT, MT and TRT performance models were developed that yielded relatively high R-squared values ($R^2$ ranged from 0.84 to 0.97).

## 6.6 Contributions of this Research

The following eight points are presented as the major contributions of this research. The main thrust of this effort was to extend the work of Fowler et al. (1991) and earlier work by adding multiple target alternatives to the aiming task, and by

increasing the number of indices of difficulty tested.

1. The effect of adding a contralateral limb to a task always affected performance. Earlier research concluded that Fitts' Law failed only for the easy target hand (Kelso et al., 1979; Marteniuk et al., 1984; Fowler et al., 1991). These conclusions were based on the slowing of the easy target hand under bimanual unequal-ID conditions when compared with unimanual and bimanual equal-ID conditions. The results presented here found that, for a given ID, MT increased when the opposite hand was tasked with increasing difficulty, and MT decreased whenever the opposite hand was tasked with a decreasing ID.

2. This research examined the choice bimanual paradigm, whereas, previously reported bimanual research did not. All effects were found to be amplified by the addition of target alternatives. RT, MT, and the difference between the unimanual and bimanual conditions increased with increasing N.

3. This research examined all combinations of he four IDs tested. Previously reported bimanual research examined an easy task versus a hard task or an easy task, a medium task, and a hard task.

4. The dependence of RT on ID was demonstrated.

5. The dependence of MT on N was demonstrated.

6. Based on the mean absolute time differences between hands, neither reaction performance nor movement performance was synchronized under the conditions tested.

7. Bimanual RT and MT models with OPID as a factor were constructed and

yielded high $R^2$ values.

8. A total response time model for bimanual and unimanual performance with a high $R^2$ was presented.

## 6.7 Suggested Areas for Future Research

Human performance under the bimanual unequal-ID paradigm needs further investigation. Much of the research using Hick and Fitts models are unimanual approximations to reality. Some validity is lost if these unimanual models are applied to real-world problems since many stimulus-response problems require bimanual responses. The bimanual model would be most appropriate in the area of the human-machine interface where fast, accurate responses are critical. The design of high-performance aircraft is one such area. However, other areas would benefit by applying a bimanual model.

Currently, research is underway to produce human-machine systems that operate under synthetic environments. Such systems would allow the human operator to be immersed in a simulated environment, artificially created, as though the person were actually living it. This synthetic environment is often referred to as "virtual reality" or "virtual space." For example, such a system might allow a surgeon to remotely perform delicate surgery from any location properly equipped. This application would have more impact than just providing convenience to the doctor. If developed, such a system could provide medical care to people for whom care would otherwise be inaccessible. If could also have applications to emergency trauma cases where little time exists for prompt

medical care. Therefore, testing Hick's Law and Fitts' Law in virtual space is an area to investigate.

On a simpler scale, the asymmetry issue needs further clarification. The work reported here did not consider location effects. Having subjects strike two targets that were not mirror images with respect to the sagittal plane implies that a spatial asymmetry existed. These effects need to be accounted for and separated from the task difficulty differences for a more complete picture.

The task used here presented simultaneous, left and right, bimanual stimuli to the subjects. If there were a small, but significant delay between one stimulus event and the other, randomized across left and right hands, a very different task would exist. Under these conditions, visual scanning patterns would probably be critical to temporal performance. Along the same lines, a test could be developed that presented a single stimulus, requiring a unimanual response at times, and dual stimuli, requiring bimanual responses at other times. After all, real-world problems seldom require the same type of response each time.

Another aspect of the bimanual task that was not addressed here concerns the individual strategies of the subjects. No subject was advised on how to strike the two targets except to be as accurate and fast as possible. Different task strategies were apparent between and within subjects. For example, some subjects concentrated on the weak hand, letting the strong hand be (apparently) kinesthetically guided. Some subjects seemed to strike targets fast with the strong hand first, then concentrated on the weak hand. Some subjects seemed to try for synchrony and simultaneous movements for all

trials. If underlying user strategy patterns could be determined, then those patterns could be applied early for optimal product design.

Since analyzing temporal measures alone can not reveal all issues of synchrony between hands under the bimanual paradigm, biomechanical analysis should be extended to the multiple target conditions tested here. This could include high-speed photography with velocity and acceleration analysis of limb reaction and movement.

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## Appendix A Subject Instructions

**TESTING HICK'S AND FITTS' LAWS**
**UNDER THE BIMANUAL PARADIGM**
**WITH UNEQUAL INDICES OF DIFFICULTY**

WELCOME!

You will be performing what is known as a **"choice reaction task"** in response to a visual stimulus. More specifically, you will be holding, in either one, or both, of your hands an aluminum stylus at the home position. The home position is the 1" circular disk centered near the side of the black target board closest to you. Each home position has blue tape around its outer side. The experimenter will tell you whether to hold the stylus on the right home position or on the left position. There will be times when you will be instructed to hold the styli on both home positions simultaneously.

Notice that there are two arcs of LED lights (4 per side) positioned on the target board. One, two, or four LED's will be illuminated in a random sequence. Each LED is positioned along a radius emanating from the home positions. These lights are relatively bright and you should have no difficulty seeing them. Notice that along each radii there are four holes at 4", 8", 12" and 16". Circular aluminum targets will be placed in the holes throughout the experiment. When you perceive that an LED has been illuminated, your task will be to move your hand with the stylus from the home position and hit the target that compliments the illuminated LED with the stylus. It is important that you be both as accurate as you can in hitting the target, and that you react to the stimulus and move to the target as quickly as you can.

After the target has been successfully hit the corresponding LED will go out. If you miss the target try to hit it again as quickly as you can. If you hit the wrong target, the LED will go out and you must move your hand back to the home position. Hitting the wrong target will be recorded as an error.

Even though you should move to the target as quickly as you can, you may take your time in returning to the home position only **after each target has been hit.** You may take advantage of this if you need to use this time for yourself. The system will wait for the styli to be on the home positions before another stimulus is presented.

There are 110 separate target/hand combinations being tested in this experiment. Each experiment involves 20 trials. Between each trial there will be a short time of inactivity on your part while the experimenter is changing the experimental conditions. You may adjust yourself, or ask any questions you may have at this time. A 10 minute break will be given after approximately 1 hour.

## Appendix B Institutional Review Board Approval

The
University of Oklahoma

OFFICE OF RESEARCH ADMINISTRATION
1000 Asp Avenue, Suite 314
Norman, Oklahoma 73019-0430
(405) 325-4757
FAX (405) 325-6029

May 7, 1992

Captain George Waltensperger
Industrial Engineering
University of Oklahoma

SUBJECT: IRB-NC Review of Proposal

Dear Captain Waltensperger:

The Institutional Review Board-Norman Campus has reviewed your proposal, "Examining Hick's and Fitts' Laws Under the Choice Bimanual Aiming Task Paradigm with Unequal Indices of Difficulty," under the University's expedited review procedures. The Board found that this research would not constitute a risk to participants beyond those of normal, everyday life, except in the area of privacy, which is adequately protected by the confidentiality procedures. Therefore, the Board has approved the use of human subjects in this research.

You must submit a report describing your use of human subjects in this research not later than twelve months from the date of this approval. Should this research be extended beyond twelve months, a progress report must be submitted not later than twelve months from this date, and a final report must be submitted at the end of the research.

Should you wish to deviate significantly from the subject research procedures described in your proposal, you must obtain prior approval from the Board.

Sincerely yours,

Karen Petry

Karen Petry
Administrative Officer -
Institutional Review Board

KP/clw

cc: Dr. Eddie Carol Smith, Chair, IRB
Dr. Robert Schlegel, Industrial Engineering

# Appendix C Informed Consent Form

**UNIVERSITY OF OKLAHOMA**

**INFORMED CONSENT FORM**

Project Title: <u>An Examination of Hick's and Fitts' Laws Under the Choice Bi-manual Aiming Task Paradigm with Unequal Indices of Difficulty</u>

Investigator: <u>George Mark Waltensperger</u>

Industrial Engineering, 325-3721, 325-3211

This is to certify that I, ______________________________ hereby agree to participate as a volunteer in a scientific experiment as part of an authorized dissertation research project of the University of Oklahoma under the supervision of Dr. Robert E. Schlegel.

The purpose of this research is to characterize and model human bi-manual aiming performance on reaction and movement time when given an imperative stimulus. When given an imperative stimulus I will move either one or both hands to the appropriate target on the target-board and touch that target, or targets, with a stylus.

I understand that I may expect minimal physical and/or mental discomfort during the course of this research. I understand that by participating in this research , I will be subjected to minimal physical, mental and/or social risks.

I understand that I am free to refuse to participate in any procedure or to refuse to answer any question at any time without any prejudice to me. I understand that I am free to withdraw my consent and to withdraw from the research at any time without any prejudice to me.

I understand that by agreeing to participate in this research and signing this form I do not waive my legal rights.

I understand that the research investigator named above will answer any of my questions relating to the research procedures at any time.

______________________________ ______________________________

Date Subject Signature

Appendix D Pilot II Mean RT and MT.

| TARGETS | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|
| 1 | 227 | 402 |
| 2 | 298 | 448 |
| 4 | 342 | 513 |

| CONDITION | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|
| BI | 339 | 574 |
| UNI | 239 | 335 |

| HAND | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|
| LEFT | 284 | 473 |
| RIGHT | 294 | 435 |

| ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|
| 3 | 274 | 277 |
| 4 | 287 | 381 |
| 5 | 281 | 475 |
| 6 | 314 | 684 |

| TARGETS | CONDITION | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | BI | 243 | 484 |
| 1 | UNI | 211 | 319 |
| 2 | BI | 347 | 549 |
| 2 | UNI | 250 | 347 |
| 4 | BI | 428 | 688 |
| 4 | UNI | 256 | 338 |

Appendix D Pilot II Mean RT and MT (cont.).

| TARGETS | HAND | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | LEFT | 225 | 417 |
| 1 | RIGHT | 230 | 386 |
| 2 | LEFT | 294 | 467 |
| 2 | RIGHT | 302 | 429 |
| 4 | LEFT | 334 | 536 |
| 4 | RIGHT | 350 | 490 |

| TARGETS | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | 3 | 215 | 224 |
| 1 | 4 | 225 | 321 |
| 1 | 5 | 227 | 429 |
| 1 | 6 | 242 | 633 |
| 2 | 3 | 279 | 263 |
| 2 | 4 | 302 | 378 |
| 2 | 5 | 298 | 481 |
| 2 | 6 | 313 | 671 |
| 4 | 3 | 329 | 344 |
| 4 | 4 | 333 | 445 |
| 4 | 5 | 317 | 514 |
| 4 | 6 | 388 | 748 |

| CONDITION | HAND | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| BI | LEFT | 334 | 595 |
| BI | RIGHT | 345 | 552 |
| UNI | LEFT | 235 | 352 |
| UNI | RIGHT | 243 | 318 |

Appendix D Pilot II Mean RT and MT (cont.).

| CONDITION | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| BI | 3 | 317 | 335 |
| BI | 4 | 338 | 476 |
| BI | 5 | 323 | 601 |
| BI | 6 | 379 | 882 |
| UNI | 3 | 231 | 218 |
| UNI | 4 | 236 | 286 |
| UNI | 5 | 239 | 348 |
| UNI | 6 | 250 | 486 |

| HAND | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| LEFT | 3 | 269 | 284 |
| LEFT | 4 | 282 | 393 |
| LEFT | 5 | 278 | 513 |
| LEFT | 6 | 308 | 705 |
| RIGHT | 3 | 279 | 270 |
| RIGHT | 4 | 291 | 370 |
| RIGHT | 5 | 284 | 437 |
| RIGHT | 6 | 321 | 663 |

| TARGETS | CONDITION | HAND | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | BI | LEFT | 241 | 501 |
| 1 | BI | RIGHT | 246 | 468 |
| 1 | UNI | LEFT | 208 | 334 |
| 1 | UNI | RIGHT | 214 | 304 |
| 2 | BI | LEFT | 341 | 566 |
| 2 | BI | RIGHT | 353 | 531 |
| 2 | UNI | LEFT | 247 | 368 |
| 2 | UNI | RIGHT | 252 | 326 |
| 4 | BI | LEFT | 419 | 719 |
| 4 | BI | RIGHT | 436 | 657 |
| 4 | UNI | LEFT | 249 | 351 |
| 4 | UNI | RIGHT | 263 | 323 |

Appendix D Pilot II Mean RT and MT (cont.).

| TARGETS | CONDITION | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | BI | 3 | 226 | 240 |
| 1 | BI | 4 | 241 | 382 |
| 1 | BI | 5 | 243 | 527 |
| 1 | BI | 6 | 263 | 789 |
| 1 | UNI | 3 | 203 | 207 |
| 1 | UNI | 4 | 208 | 260 |
| 1 | UNI | 5 | 211 | 332 |
| 1 | UNI | 6 | 222 | 477 |
| 2 | BI | 3 | 318 | 298 |
| 2 | BI | 4 | 355 | 442 |
| 2 | BI | 5 | 346 | 601 |
| 2 | BI | 6 | 367 | 854 |
| 2 | UNI | 3 | 240 | 228 |
| 2 | UNI | 4 | 249 | 314 |
| 2 | UNI | 5 | 251 | 360 |
| 2 | UNI | 6 | 259 | 487 |
| 4 | BI | 3 | 407 | 468 |
| 4 | BI | 4 | 417 | 605 |
| 4 | BI | 5 | 380 | 674 |
| 4 | BI | 6 | 508 | 1003 |
| 4 | UNI | 3 | 251 | 219 |
| 4 | UNI | 4 | 250 | 284 |
| 4 | UNI | 5 | 255 | 354 |
| 4 | UNI | 6 | 268 | 494 |

Appendix D Pilot II Mean RT and MT (cont.).

| TARGETS | HAND | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | LEFT | 3 | 213 | 232 |
| 1 | LEFT | 4 | 223 | 333 |
| 1 | LEFT | 5 | 225 | 451 |
| 1 | LEFT | 6 | 237 | 654 |
| 1 | RIGHT | 3 | 216 | 216 |
| 1 | RIGHT | 4 | 226 | 309 |
| 1 | RIGHT | 5 | 230 | 408 |
| 1 | RIGHT | 6 | 247 | 611 |
| 2 | LEFT | 3 | 270 | 277 |
| 2 | LEFT | 4 | 301 | 388 |
| 2 | LEFT | 5 | 300 | 523 |
| 2 | LEFT | 6 | 306 | 682 |
| 2 | RIGHT | 3 | 288 | 249 |
| 2 | RIGHT | 4 | 304 | 368 |
| 2 | RIGHT | 5 | 297 | 439 |
| 2 | RIGHT | 6 | 320 | 660 |
| 4 | LEFT | 3 | 323 | 343 |
| 4 | LEFT | 4 | 322 | 458 |
| 4 | LEFT | 5 | 310 | 564 |
| 4 | LEFT | 6 | 381 | 778 |
| 4 | RIGHT | 3 | 335 | 345 |
| 4 | RIGHT | 4 | 344 | 432 |
| 4 | RIGHT | 5 | 325 | 464 |
| 4 | RIGHT | 6 | 395 | 719 |

| CONDITION | HAND | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| BI | LEFT | 3 | 311 | 338 |
| BI | LEFT | 4 | 332 | 482 |
| BI | LEFT | 5 | 319 | 650 |
| BI | LEFT | 6 | 372 | 911 |
| BI | RIGHT | 3 | 323 | 333 |
| BI | RIGHT | 4 | 343 | 470 |
| BI | RIGHT | 5 | 327 | 552 |
| BI | RIGHT | 6 | 386 | 853 |
| UNI | LEFT | 3 | 226 | 229 |
| UNI | LEFT | 4 | 232 | 303 |
| UNI | LEFT | 5 | 237 | 375 |
| UNI | LEFT | 6 | 244 | 498 |
| UNI | RIGHT | 3 | 236 | 207 |
| UNI | RIGHT | 4 | 239 | 269 |
| UNI | RIGHT | 5 | 241 | 322 |
| UNI | RIGHT | 6 | 255 | 474 |

Appendix D Pilot II Mean RT and MT (cont.).

| TARGETS | CONDITION | HAND | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|---|
| 4 | BI | LEFT | 3 | 399 | 461 |
| 4 | BI | LEFT | 4 | 408 | 614 |
| 4 | BI | LEFT | 5 | 372 | 756 |
| 4 | BI | LEFT | 6 | 499 | 1042 |
| 4 | BI | RIGHT | 3 | 415 | 474 |
| 4 | BI | RIGHT | 4 | 425 | 597 |
| 4 | BI | RIGHT | 5 | 387 | 593 |
| 4 | BI | RIGHT | 6 | 517 | 963 |
| 4 | UNI | LEFT | 3 | 248 | 224 |
| 4 | UNI | LEFT | 4 | 237 | 302 |
| 4 | UNI | LEFT | 5 | 248 | 371 |
| 4 | UNI | LEFT | 6 | 263 | 514 |
| 4 | UNI | RIGHT | 3 | 255 | 215 |
| 4 | UNI | RIGHT | 4 | 264 | 267 |
| 4 | UNI | RIGHT | 5 | 262 | 336 |
| 4 | UNI | RIGHT | 6 | 274 | 474 |

Appendix D Pilot II Mean RT and MT (cont.).

| TARGETS | CONDITION | HAND | ID | PILOT STUDY II MEAN REACTION TIME (msec) | PILOT STUDY II MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|---|
| 1 | BI | LEFT | 3 | 225 | 243 |
| 1 | BI | LEFT | 4 | 238 | 388 |
| 1 | BI | LEFT | 5 | 242 | 556 |
| 1 | BI | LEFT | 6 | 258 | 817 |
| 1 | BI | RIGHT | 3 | 227 | 238 |
| 1 | BI | RIGHT | 4 | 245 | 375 |
| 1 | BI | RIGHT | 5 | 245 | 498 |
| 1 | BI | RIGHT | 6 | 268 | 761 |
| 1 | UNI | LEFT | 3 | 201 | 220 |
| 1 | UNI | LEFT | 4 | 209 | 278 |
| 1 | UNI | LEFT | 5 | 207 | 346 |
| 1 | UNI | LEFT | 6 | 217 | 491 |
| 1 | UNI | RIGHT | 3 | 205 | 194 |
| 1 | UNI | RIGHT | 4 | 208 | 243 |
| 1 | UNI | RIGHT | 5 | 215 | 318 |
| 1 | UNI | RIGHT | 6 | 227 | 462 |
| 2 | BI | LEFT | 3 | 310 | 309 |
| 2 | BI | LEFT | 4 | 351 | 445 |
| 2 | BI | LEFT | 5 | 343 | 638 |
| 2 | BI | LEFT | 6 | 360 | 873 |
| 2 | BI | RIGHT | 3 | 327 | 286 |
| 2 | BI | RIGHT | 4 | 360 | 439 |
| 2 | BI | RIGHT | 5 | 348 | 565 |
| 2 | BI | RIGHT | 6 | 375 | 836 |
| 2 | UNI | LEFT | 3 | 230 | 244 |
| 2 | UNI | LEFT | 4 | 251 | 331 |
| 2 | UNI | LEFT | 5 | 256 | 408 |
| 2 | UNI | LEFT | 6 | 253 | 490 |
| 2 | UNI | RIGHT | 3 | 249 | 212 |
| 2 | UNI | RIGHT | 4 | 247 | 297 |
| 2 | UNI | RIGHT | 5 | 246 | 313 |
| 2 | UNI | RIGHT | 6 | 265 | 484 |

Appendix E Mean RT and MT For All Conditions.

| TARGETS | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| 1 | 244 | 415 |
| 2 | 316 | 458 |
| 4 | 356 | 482 |

| CONDITION | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| BI | 364 | 550 |
| UNI | 247 | 353 |

| HAND | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| LEFT | 305 | 469 |
| RIGHT | 306 | 434 |

| ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| 3 | 278 | 283 |
| 4 | 286 | 362 |
| 5 | 328 | 518 |
| 6 | 330 | 645 |

| TARGETS | CONDITION | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | BI | 261 | 493 |
| 1 | UNI | 227 | 337 |
| 2 | BI | 181 | [illegible] |
| 2 | UNI | 250 | 357 |
| 4 | BI | 448 | 599 |
| 4 | UNI | 264 | 366 |

Appendix E  Mean RT and MT For All Conditions (cont.).

| TARGETS | HAND | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | LEFT | 244 | 431 |
| 1 | RIGHT | 244 | 398 |
| 2 | LEFT | 315 | 476 |
| 2 | RIGHT | 318 | 440 |
| 4 | LEFT | 357 | 501 |
| 4 | RIGHT | 355 | 464 |

| TARGETS | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | 3 | 227 | 251 |
| 1 | 4 | 239 | 324 |
| 1 | 5 | 254 | 465 |
| 1 | 6 | 256 | 620 |
| 2 | 3 | 288 | 282 |
| 2 | 4 | 291 | 373 |
| 2 | 5 | 336 | 530 |
| 2 | 6 | 350 | 646 |
| 4 | 3 | 319 | 314 |
| 4 | 4 | 328 | 389 |
| 4 | 5 | 396 | 558 |
| 4 | 6 | 383 | 669 |

| CONDITION | HAND | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| BI | LEFT | 366 | 567 |
| BI | RIGHT | 362 | 533 |
| UNI | LEFT | 244 | 372 |
| UNI | RIGHT | 250 | 335 |

Appendix E Mean RT and MT For All Conditions (cont.).

| CONDITION | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| BI | 3 | 319 | 321 |
| BI | 4 | 331 | 440 |
| BI | 5 | 403 | 645 |
| BI | 6 | 403 | 794 |
| UNI | 3 | 237 | 244 |
| UNI | 4 | 241 | 283 |
| UNI | 5 | 253 | 391 |
| UNI | 6 | 256 | 496 |

| HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| LEFT | 3 | 276 | 294 |
| LEFT | 4 | 284 | 373 |
| LEFT | 5 | 324 | 538 |
| LEFT | 6 | 337 | 674 |
| RIGHT | 3 | 279 | 271 |
| RIGHT | 4 | 288 | 351 |
| RIGHT | 5 | 333 | 498 |
| RIGHT | 6 | 323 | 616 |

| TARGETS | CONDITION | HAND | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | BI | LEFT | 260 | 506 |
| 1 | BI | RIGHT | 262 | 479 |
| 1 | UNI | LEFT | 228 | 357 |
| 1 | UNI | RIGHT | 227 | 317 |
| 2 | BI | LEFT | 385 | 576 |
| 2 | BI | RIGHT | 381 | 541 |
| 2 | UNI | LEFT | 245 | 376 |
| 2 | UNI | RIGHT | 255 | 338 |
| 4 | BI | LEFT | 453 | 618 |
| 4 | BI | RIGHT | 441 | 579 |
| 4 | UNI | LEFT | 260 | 383 |
| 4 | UNI | RIGHT | 268 | 350 |

Appendix E  Mean RT and MT For All Conditions (cont.).

| TARGETS | CONDITION | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | BI | 3 | 237 | 272 |
| 1 | BI | 4 | 258 | 377 |
| 1 | BI | 5 | 274 | 563 |
| 1 | BI | 6 | 274 | 758 |
| 1 | UNI | 3 | 217 | 231 |
| 1 | UNI | 4 | 220 | 270 |
| 1 | UNI | 5 | 233 | 366 |
| 1 | UNI | 6 | 239 | 482 |
| 2 | BI | 3 | 336 | 319 |
| 2 | BI | 4 | 337 | 457 |
| 2 | BI | 5 | 417 | 661 |
| 2 | BI | 6 | 441 | 798 |
| 2 | UNI | 3 | 240 | 246 |
| 2 | UNI | 4 | 245 | 288 |
| 2 | UNI | 5 | 255 | 400 |
| 2 | UNI | 6 | 259 | 495 |
| 4 | BI | 3 | 383 | 373 |
| 4 | BI | 4 | 396 | 487 |
| 4 | BI | 5 | 519 | 710 |
| 4 | BI | 6 | 495 | 825 |
| 4 | UNI | 3 | 254 | 255 |
| 4 | UNI | 4 | 259 | 291 |
| 4 | UNI | 5 | 272 | 406 |
| 4 | UNI | 6 | 270 | 513 |

Appendix E  Mean RT and MT For All Conditions (cont.).

| TARGETS | HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | LEFT | 3 | 227 | 265 |
| 1 | LEFT | 4 | 239 | 333 |
| 1 | LEFT | 5 | 255 | 488 |
| 1 | LEFT | 6 | 256 | 639 |
| 1 | RIGHT | 3 | 228 | 238 |
| 1 | RIGHT | 4 | 240 | 314 |
| 1 | RIGHT | 5 | 252 | 441 |
| 1 | RIGHT | 6 | 256 | 600 |
| 2 | LEFT | 3 | 283 | 291 |
| 2 | LEFT | 4 | 290 | 383 |
| 2 | LEFT | 5 | 328 | 540 |
| 2 | LEFT | 6 | 358 | 691 |
| 2 | RIGHT | 3 | 293 | 274 |
| 2 | RIGHT | 4 | 292 | 362 |
| 2 | RIGHT | 5 | 343 | 520 |
| 2 | RIGHT | 6 | 343 | 602 |
| 4 | LEFT | 3 | 320 | 325 |
| 4 | LEFT | 4 | 323 | 401 |
| 4 | LEFT | 5 | 389 | 584 |
| 4 | LEFT | 6 | 396 | 692 |
| 4 | RIGHT | 3 | 318 | 303 |
| 4 | RIGHT | 4 | 332 | 376 |
| 4 | RIGHT | 5 | 403 | 532 |
| 4 | RIGHT | 6 | 369 | 646 |

| CONDITION | HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| BI | LEFT | 3 | 319 | 329 |
| BI | LEFT | 4 | 331 | 446 |
| BI | LEFT | 5 | 396 | 668 |
| BI | LEFT | 6 | 419 | 825 |
| BI | RIGHT | 3 | 318 | 314 |
| BI | RIGHT | 4 | 330 | 415 |
| BI | RIGHT | 5 | 411 | 622 |
| BI | RIGHT | 6 | 388 | 762 |
| UNI | LEFT | 3 | 233 | 259 |
| UNI | LEFT | 4 | 237 | 299 |
| UNI | LEFT | 5 | 252 | 407 |
| UNI | LEFT | 6 | 254 | 523 |
| UNI | RIGHT | 3 | 240 | 229 |
| UNI | RIGHT | 4 | 246 | 267 |
| UNI | RIGHT | 5 | 255 | 374 |
| UNI | RIGHT | 6 | 258 | 470 |

Appendix E Mean RT and MT For All Conditions (cont.)

| TARGETS | CONDITION | HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|---|
| 1 | BI | LEFT | 3 | 236 | 279 |
| 1 | BI | LEFT | 4 | 258 | 377 |
| 1 | BI | LEFT | 5 | 275 | 598 |
| 1 | BI | LEFT | 6 | 272 | 768 |
| 1 | BI | RIGHT | 3 | 238 | 265 |
| 1 | BI | RIGHT | 4 | 259 | 377 |
| 1 | BI | RIGHT | 5 | 273 | 528 |
| 1 | BI | RIGHT | 6 | 276 | 748 |
| 1 | UNI | LEFT | 3 | 218 | 251 |
| 1 | UNI | LEFT | 4 | 220 | 290 |
| 1 | UNI | LEFT | 5 | 235 | 379 |
| 1 | UNI | LEFT | 6 | 241 | 510 |
| 1 | UNI | RIGHT | 3 | 217 | 211 |
| 1 | UNI | RIGHT | 4 | 220 | 251 |
| 1 | UNI | RIGHT | 5 | 232 | 353 |
| 1 | UNI | RIGHT | 6 | 237 | 453 |
| 2 | BI | LEFT | 3 | 333 | 323 |
| 2 | BI | LEFT | 4 | 343 | 461 |
| 2 | BI | LEFT | 5 | 403 | 664 |
| 2 | BI | LEFT | 6 | 461 | 858 |
| 2 | BI | RIGHT | 3 | 339 | 315 |
| 2 | BI | RIGHT | 4 | 332 | 453 |
| 2 | BI | RIGHT | 5 | 431 | 658 |
| 2 | BI | RIGHT | 6 | 422 | 737 |
| 2 | UNI | LEFT | 3 | 233 | 258 |
| 2 | UNI | LEFT | 4 | 238 | 305 |
| 2 | UNI | LEFT | 5 | 253 | 417 |
| 2 | UNI | LEFT | 6 | 255 | 523 |
| 2 | UNI | RIGHT | 3 | 247 | 233 |
| 2 | UNI | RIGHT | 4 | 252 | 271 |
| 2 | UNI | RIGHT | 5 | 256 | 382 |
| 2 | UNI | RIGHT | 6 | 264 | 467 |

Appendix E Mean RT and MT For All Conditions (cont.

| TARGETS | CONDITION | HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|---|
| 4 | BI | LEFT | 3 | 389 | 383 |
| 4 | BI | LEFT | 4 | 392 | 499 |
| 4 | BI | LEFT | 5 | 509 | 742 |
| 4 | BI | LEFT | 6 | 524 | 849 |
| 4 | BI | RIGHT | 3 | 378 | 362 |
| 4 | BI | RIGHT | 4 | 400 | 474 |
| 4 | BI | RIGHT | 5 | 530 | 679 |
| 4 | BI | RIGHT | 6 | 466 | 801 |
| 4 | UNI | LEFT | 3 | 250 | 267 |
| 4 | UNI | LEFT | 4 | 253 | 303 |
| 4 | UNI | LEFT | 5 | 268 | 426 |
| 4 | UNI | LEFT | 6 | 268 | 534 |
| 4 | UNI | RIGHT | 3 | 257 | 243 |
| 4 | UNI | RIGHT | 4 | 265 | 278 |
| 4 | UNI | RIGHT | 5 | 276 | 386 |
| 4 | UNI | RIGHT | 6 | 272 | 491 |

Appendix F Main Unimanual Mean RT and MT.

| TARGETS | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| 1 | 227 | 337 |
| 2 | 250 | 357 |
| 4 | 264 | 366 |

| HAND | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| LEFT | 244 | 372 |
| RIGHT | 250 | 335 |

| ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|
| 3 | 237 | 244 |
| 4 | 241 | 283 |
| 5 | 253 | 391 |
| 6 | 256 | 496 |

| TARGETS | HAND | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | LEFT | 228 | 357 |
| 1 | RIGHT | 227 | 317 |
| 2 | LEFT | 245 | 376 |
| 2 | RIGHT | 255 | 338 |
| 4 | LEFT | 260 | 383 |
| 4 | RIGHT | 268 | 350 |

Appendix F Main Unimanual Mean RT and MT (cont.

| TARGETS | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| 1 | 3 | 217 | 231 |
| 1 | 4 | 220 | 270 |
| 1 | 5 | 233 | 366 |
| 1 | 6 | 239 | 482 |
| 2 | 3 | 240 | 246 |
| 2 | 4 | 245 | 288 |
| 2 | 5 | 255 | 400 |
| 2 | 6 | 259 | 495 |
| 4 | 3 | 254 | 255 |
| 4 | 4 | 259 | 291 |
| 4 | 5 | 272 | 406 |
| 4 | 6 | 270 | 513 |

| HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|
| LEFT | 3 | 233 | 259 |
| LEFT | 4 | 237 | 299 |
| LEFT | 5 | 252 | 407 |
| LEFT | 6 | 254 | 523 |
| RIGHT | 3 | 240 | 229 |
| RIGHT | 4 | 246 | 267 |
| RIGHT | 5 | 255 | 374 |
| RIGHT | 6 | 258 | 470 |

Appendix F Main Unimanual Mean RT and MT (cont).

| TARGETS | HAND | ID | MAIN - MEAN REACTION TIME (msec) | MAIN - MEAN MOVEMENT TIME (msec) |
|---|---|---|---|---|
| 1 | LEFT | 3 | 218 | 251 |
| 1 | LEFT | 4 | 220 | 290 |
| 1 | LEFT | 5 | 235 | 379 |
| 1 | LEFT | 6 | 241 | 510 |
| 1 | RIGHT | 3 | 217 | 211 |
| 1 | RIGHT | 4 | 220 | 251 |
| 1 | RIGHT | 5 | 232 | 353 |
| 1 | RIGHT | 6 | 237 | 453 |
| 2 | LEFT | 3 | 233 | 258 |
| 2 | LEFT | 4 | 238 | 305 |
| 2 | LEFT | 5 | 253 | 417 |
| 2 | LEFT | 6 | 255 | 523 |
| 2 | RIGHT | 3 | 247 | 233 |
| 2 | RIGHT | 4 | 252 | 271 |
| 2 | RIGHT | 5 | 256 | 382 |
| 2 | RIGHT | 6 | 264 | 467 |
| 4 | LEFT | 3 | 250 | 267 |
| 4 | LEFT | 4 | 253 | 303 |
| 4 | LEFT | 5 | 268 | 426 |
| 4 | LEFT | 6 | 268 | 534 |
| 4 | RIGHT | 3 | 257 | 243 |
| 4 | RIGHT | 4 | 265 | 278 |
| 4 | RIGHT | 5 | 276 | 386 |
| 4 | RIGHT | 6 | 272 | 491 |

## Appendix G Main Study Mean RT Equal-ID vs. Unequal-ID.

| TARGETS | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|
| 1 | 250 | 255 | 267 | 276 |
| 2 | 344 | 351 | 393 | 406 |
| 4 | 406 | 400 | 477 | 468 |

| HAND | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|
| LEFT | 333 | 338 | 377 | 383 |
| RIGHT | 334 | 333 | 381 | 383 |

| OPPOSITE ID | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|
| 3 | 319 | 319 | 347 | 359 |
| 4 | 321 | 331 | 370 | 371 |
| 5 | 342 | 345 | 403 | 400 |
| 6 | 352 | 346 | 396 | 403 |

| TARGETS | HAND | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|---|
| 1 | LEFT | 249 | 256 | 268 | 271 |
| 1 | RIGHT | 251 | 254 | 266 | 280 |
| 2 | LEFT | 347 | 357 | 391 | 404 |
| 2 | RIGHT | 342 | 344 | 396 | 408 |
| 4 | LEFT | 403 | 400 | 473 | 475 |
| 4 | RIGHT | 408 | 400 | 481 | 461 |

Appendix G Main Study Mean RT Equal-ID vs. Unequal-ID (cont.).

| TARGETS | OPPOSITE ID | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|---|
| 1 | 3 | 237 | 244 | 251 | 267 |
| 1 | 4 | 246 | 258 | 266 | 281 |
| 1 | 5 | 250 | 256 | 274 | 280 |
| 1 | 6 | 268 | 262 | 278 | 274 |
| 2 | 3 | 336 | 332 | 358 | 381 |
| 2 | 4 | 336 | 337 | 387 | 389 |
| 2 | 5 | 351 | 367 | 417 | 413 |
| 2 | 6 | 354 | 367 | 412 | 441 |
| 4 | 3 | 383 | 382 | 431 | 428 |
| 4 | 4 | 381 | 396 | 456 | 442 |
| 4 | 5 | 426 | 413 | 519 | 507 |
| 4 | 6 | 432 | 410 | 500 | 495 |

| HAND | OPPOSITE ID | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|---|
| LEFT | 3 | 319 | 325 | 342 | 358 |
| LEFT | 4 | 319 | 331 | 368 | 361 |
| LEFT | 5 | 343 | 350 | 396 | 396 |
| LEFT | 6 | 352 | 346 | 402 | 419 |
| RIGHT | 3 | 318 | 314 | 351 | 360 |
| RIGHT | 4 | 323 | 330 | 372 | 381 |
| RIGHT | 5 | 342 | 341 | 411 | 404 |
| RIGHT | 6 | 351 | 347 | 391 | 388 |

Appendix G Main Study Mean RT Equal-ID vs. Unequal-ID (cont.).

| TARGETS | HAND | OPPOSITE ID | MAIN - MEAN REACTION TIME (msec) INDEX=3 | MAIN - MEAN REACTION TIME (msec) INDEX=4 | MAIN - MEAN REACTION TIME (msec) INDEX=5 | MAIN - MEAN REACTION TIME (msec) INDEX=6 |
|---|---|---|---|---|---|---|
| 1 | LEFT | 3 | 236 | 245 | 251 | 267 |
| 1 | LEFT | 4 | 244 | 258 | 264 | 275 |
| 1 | LEFT | 5 | 251 | 256 | 275 | 269 |
| 1 | LEFT | 6 | 267 | 265 | 281 | 272 |
| 1 | RIGHT | 3 | 238 | 244 | 250 | 268 |
| 1 | RIGHT | 4 | 248 | 259 | 268 | 287 |
| 1 | RIGHT | 5 | 249 | 255 | 273 | 290 |
| 1 | RIGHT | 6 | 270 | 259 | 274 | 276 |
| 2 | LEFT | 3 | 333 | 337 | 351 | 372 |
| 2 | LEFT | 4 | 336 | 343 | 379 | 379 |
| 2 | LEFT | 5 | 353 | 367 | 403 | 405 |
| 2 | LEFT | 6 | 365 | 382 | 430 | 461 |
| 2 | RIGHT | 3 | 339 | 326 | 365 | 391 |
| 2 | RIGHT | 4 | 336 | 332 | 396 | 400 |
| 2 | RIGHT | 5 | 348 | 366 | 431 | 421 |
| 2 | RIGHT | 6 | 343 | 353 | 394 | 422 |
| 4 | LEFT | 3 | 389 | 393 | 425 | 436 |
| 4 | LEFT | 4 | 376 | 392 | 461 | 428 |
| 4 | LEFT | 5 | 424 | 426 | 509 | 513 |
| 4 | LEFT | 6 | 424 | 391 | 495 | 524 |
| 4 | RIGHT | 3 | 378 | 371 | 438 | 420 |
| 4 | RIGHT | 4 | 385 | 400 | 452 | 457 |
| 4 | RIGHT | 5 | 428 | 400 | 530 | 500 |
| 4 | RIGHT | 6 | 441 | 429 | 505 | 466 |

## Appendix H Main Study Mean MT Equal-ID vs. Unequal-ID.

| TARGETS | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|
| 1 | 350 | 404 | 546 | 623 |
| 2 | 401 | 465 | 616 | 693 |
| 4 | 435 | 478 | 670 | 749 |

| HAND | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|
| LEFT | 395 | 464 | 625 | 712 |
| RIGHT | 395 | 434 | 596 | 665 |

| OPPOSITE ID | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|
| 3 | 321 | 378 | 508 | 590 |
| 4 | 372 | 440 | 592 | 659 |
| 5 | 425 | 480 | 645 | 711 |
| 6 | 463 | 496 | 698 | 794 |

| TARGETS | HAND | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|---|
| 1 | LEFT | 340 | 417 | 568 | 644 |
| 1 | RIGHT | 360 | 391 | 524 | 603 |
| 2 | LEFT | 402 | 480 | 622 | 728 |
| 2 | RIGHT | 400 | 450 | 610 | 658 |
| 4 | LEFT | 444 | 494 | 686 | 765 |
| 4 | RIGHT | 426 | 461 | 654 | 733 |

Appendix H Main Study Mean MT Equal-ID vs. Unequal-ID (cont.).

| TARGETS | OPPOSITE ID | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|---|
| 1 | 3 | 272 | 323 | 427 | 514 |
| 1 | 4 | 319 | 377 | 548 | 588 |
| 1 | 5 | 375 | 443 | 563 | 634 |
| 1 | 6 | 435 | 473 | 646 | 758 |
| 2 | 3 | 319 | 388 | 508 | 589 |
| 2 | 4 | 379 | 457 | 598 | 661 |
| 2 | 5 | 430 | 516 | 661 | 724 |
| 2 | 6 | 476 | 498 | 697 | 798 |
| 4 | 3 | 373 | 425 | 589 | 668 |
| 4 | 4 | 418 | 487 | 629 | 728 |
| 4 | 5 | 470 | 480 | 710 | 774 |
| 4 | 6 | 479 | 518 | 750 | 825 |

| HAND | OPPOSITE ID | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|---|
| LEFT | 3 | 329 | 397 | 531 | 613 |
| LEFT | 4 | 366 | 446 | 603 | 673 |
| LEFT | 5 | 419 | 494 | 668 | 738 |
| LEFT | 6 | 469 | 517 | 698 | 825 |
| RIGHT | 3 | 314 | 359 | 485 | 568 |
| RIGHT | 4 | 379 | 435 | 581 | 645 |
| RIGHT | 5 | 431 | 466 | 622 | 683 |
| RIGHT | 6 | 458 | 476 | 697 | 762 |

Appendix H Main Study Mean MT Equal-ID vs. Unequal-ID cont.).

| TARGETS | HAND | OPPOSITE ID | MAIN - MEAN MOVEMENT TIME (msec) INDEX=3 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=4 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=5 | MAIN - MEAN MOVEMENT TIME (msec) INDEX=6 |
|---|---|---|---|---|---|---|
| 1 | LEFT | 3 | 279 | 346 | 446 | 549 |
| 1 | LEFT | 4 | 303 | 377 | 565 | 595 |
| 1 | LEFT | 5 | 363 | 456 | 598 | 664 |
| 1 | LEFT | 6 | 415 | 487 | 663 | 768 |
| 1 | RIGHT | 3 | 265 | 299 | 408 | 479 |
| 1 | RIGHT | 4 | 336 | 377 | 531 | 581 |
| 1 | RIGHT | 5 | 387 | 430 | 528 | 604 |
| 1 | RIGHT | 6 | 455 | 458 | 629 | 748 |
| 2 | LEFT | 3 | 323 | 405 | 536 | 612 |
| 2 | LEFT | 4 | 372 | 461 | 609 | 687 |
| 2 | LEFT | 5 | 426 | 527 | 664 | 756 |
| 2 | LEFT | 6 | 487 | 527 | 679 | 858 |
| 2 | RIGHT | 3 | 315 | 371 | 480 | 567 |
| 2 | RIGHT | 4 | 386 | 453 | 588 | 636 |
| 2 | RIGHT | 5 | 434 | 505 | 658 | 692 |
| 2 | RIGHT | 6 | 465 | 470 | 715 | 737 |
| 4 | LEFT | 3 | 383 | 441 | 611 | 678 |
| 4 | LEFT | 4 | 421 | 499 | 636 | 737 |
| 4 | LEFT | 5 | 468 | 497 | 742 | 795 |
| 4 | LEFT | 6 | 504 | 538 | 753 | 849 |
| 4 | RIGHT | 3 | 362 | 408 | 568 | 658 |
| 4 | RIGHT | 4 | 415 | 474 | 623 | 719 |
| 4 | RIGHT | 5 | 471 | 463 | 679 | 753 |
| 4 | RIGHT | 6 | 454 | 499 | 747 | 801 |



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